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MASTER DEGREE IN CIVIL ENGINEERING

WATER ENGINEERING

Structural Vulnerability Assessment of Water Distribution Networks under Valve Closure Transients

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Amen. And long live Colombia.

Abstract

Transient flow in water distribution systems refers to the hydraulic response that occurs when a system operating under steady-state conditions is subjected to a disturbance and evolves toward a new equilibrium state. During this process, significant pressure fluctuations may develop throughout the network, potentially compromising the structural integrity and operational reliability of hydraulic infrastructure. The assessment of these phenomena is therefore essential for the identification of vulnerable components and the development of appropriate mitigation strategies.

This thesis presents an integrated methodology for assessing the structural vulnerability of water distribution networks subjected to valve closure transients. The proposed workflow combines steady-state hydraulic modelling in EPANET, transient simulations using TSNet, Python-based post-processing and GIS visualization to transform transient pressure results into structural performance indicators. Maximum transient pressures are assigned to individual pipelines, converted into circumferential (hoop) stresses, and compared with material-dependent allowable and resistant stresses to evaluate structural demand throughout the network.

The methodology was applied to a calibrated water distribution network considering representative operating conditions and multiple valve closure strategies, including both conventional linear and staged closure laws. The results demonstrate that the valve operating strategy has a significant influence on both hydraulic and structural responses. While increasing the closure time progressively reduces transient pressures, staged valve closure strategies provide an even greater reduction in structural demand. Furthermore, the analyses show that the pipelines experiencing the highest transient pressures are not necessarily those exhibiting the greatest structural vulnerability, highlighting the importance of incorporating material properties and pipe geometry into the assessment.

The proposed methodology provides a practical framework for integrating hydraulic transient simulations with structural assessment and spatial analysis, supporting the identification of vulnerable pipelines and facilitating operational decision-making, maintenance planning and asset management in water distribution systems.

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1. Introduction

Water distribution systems constitute one of the most critical components of the urban infrastructure, they ensure the delivery of drinking water from treatment facilities to consumers under different operating conditions. The design and operation of these systems are possible because of hydraulic analyses that can represent the behavior of flows and pressures throughout the network.

While conventional hydraulic analyses are generally performed under steady-state assumptions, real systems are continuously subject to operational changes that can generate transient flow conditions. These transients may produce, among other things, significant pressure fluctuations capable of affecting the structural integrity and the reliability of the system. Consequently, the analysis of transient events has become an essential aspect for the design, operation and management of water distribution networks.

This chapter introduces the general context of the research by presenting the fundamentals of water distribution systems, discussing the limitations of steady-state hydraulic analysis and presenting the need for transient flow modelling. Finally, the objectives and overall organization of the thesis are presented.

1.1 Background on Water Distribution Systems

Water distribution networks constitute the final stage of urban water supply systems [1], they usually work by transporting water from storage reservoirs to consumers through several hydraulic elements that work together to convey water throughout the service area maintaining adequate flow rates, pressures and quality [1]. As critical components of urban infrastructure, they must ensure a continuous, reliable and efficient supply of drinking water under a wide range of operating conditions such as variations in demands and different configurations of valve and pumping elements.

The principal components include storage reservoirs, pumping stations, transmission and distribution pipelines, junctions nodes, pressure and flow regulation devices such as valves, and consumer demand nodes. Each of these components performs a specific hydraulic function and contributes to the overall performance and reliability of the system. [2]

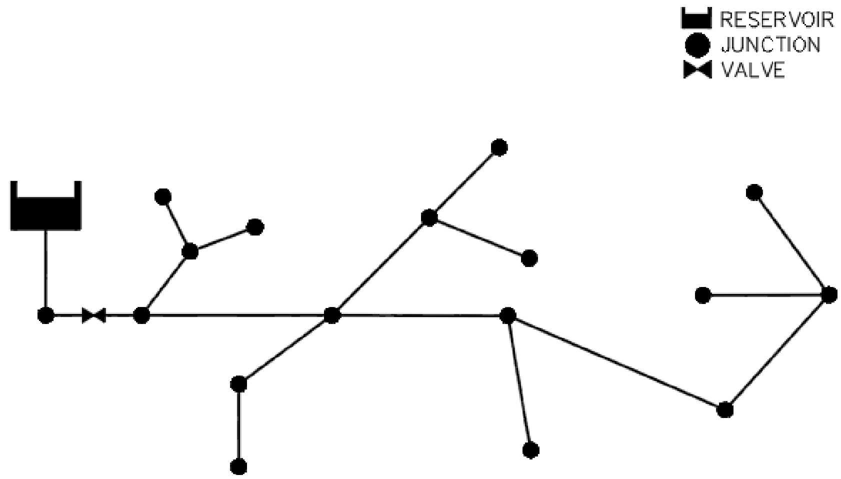


Figure 1.1Typical branched WDN

The behavior of the system is governed by the interaction between its physical characteristics and the imposed operating conditions [1]. Pipe diameter, length, material properties, internal roughness, networks topology and elevations influence the movement of water along the system, while operational variables such as demand, pumps operation and valves settings continuously modify the hydraulic conditions. Due to this, the relationships among flow, pressure, velocity and hydraulic head must be comprehended for adequate design and operation of the system.

From an engineering perspective, the primary objective of WDNs is not only to satisfy consumers water demand but also to do so while maintaining acceptable pressure levels, minimizing energy consumption, preserving water quality and ensuring long term infrastructure reliability. [1]

The following section introduces the conventional hydraulic approaches commonly used for the analysis of water distribution systems and discusses the assumptions upon which these methods are based.

1.2 Hydraulic Analysis of Water Distribution Systems

The design and operation of water distribution networks rely on hydraulic analyses capable of predicting the distribution of flow rates, pressures and hydraulics heads throughout the system [1]. These analyses provide engineers with the necessary information to dimension the infrastructure components, evaluate system performance, verify service conditions and support operational decision-making under different demand scenarios.

The hydraulic behavior of pressurized pipe networks is governed by the fundamental principles of conservation of mass and energy. At each junction within the network, the continuity equation(1.1) requires that the sum of inflows and outflows equals the water demand at the node. Simultaneously the conservation of energy, expressed by the Bernoulli equation(1.2), describes the relationship between pressure head, elevation head, and kinetic head along the system [1]. In real life networks energy losses caused by pipe friction and local hydraulic elements must also be considered, making head loss equation an essential component of hydraulic analysis.

$$\sum Q_{in} - \sum Q_{out} = 0 \tag{1.1}$$

$$z_{us} + \frac{P_{us}}{\gamma} + \frac{{V_{us}}^2}{2g} = z_{DS} + \frac{P_{DS}}{\gamma} + \frac{{V_{DS}}^2}{2g} + h_f \tag{1.2}$$

Several empirical and semi-empirical formulations have been developed to estimate friction losses h_f in pressurized pipelines, among which the Darcy-Weisbach and Hazen-Williams equations are the most widely applied [1].

The increasing complexity of modern WDS has led to the use of numerical simulation tools capable of solving large networks efficiently. One of the most used is *EPANET*, which performs extended-period and steady state simulations by solving continuity and mass conservation equations for every element of the network [3], this is useful for engineers to evaluate different operational conditions and infrastructures performance to support decision making in the design and management of the systems.

Although these hydraulic analyses provide an accurate representation of the network behavior under equilibrium conditions, they assume that hydraulic variables remain constant during each analyzed state, consequently, they do not describe the hydraulic process that occurs while the system evolves from one operating condition to another [4]. These transitional processes require a different analytical framework, a transient flow analysis, which will be introduced in the following section

1.3 Steady-State vs Transient Flow Analyses

Steady-state hydraulic analysis has long been established as the standard approach for the design and operation of water distribution networks. By assuming that hydraulic variables remain constant with time, this approach provides reliable estimates of flow rates, pressures, and hydraulic heads under equilibrium operating conditions. [1]

Despite its widespread application, the steady-state assumption represents an idealized condition that does not fully describe the dynamic behavior of real water distribution systems.

In practice, hydraulic networks are continuously subjected to operational changes generating a transition between two equilibrium states rather than an instantaneous change.

During this transition, pressure and flow conditions evolve continuously throughout the network as pressure waves propagate along the pipelines [4]. These short-duration phenomena cannot be represented using conventional steady-state analyses, since the governing equations assume that all hydraulic variables remain constant during the analyzed time condition t_n. As a result, potentially critical pressure fluctuations may remain undetected if only steady-state simulations are considered.

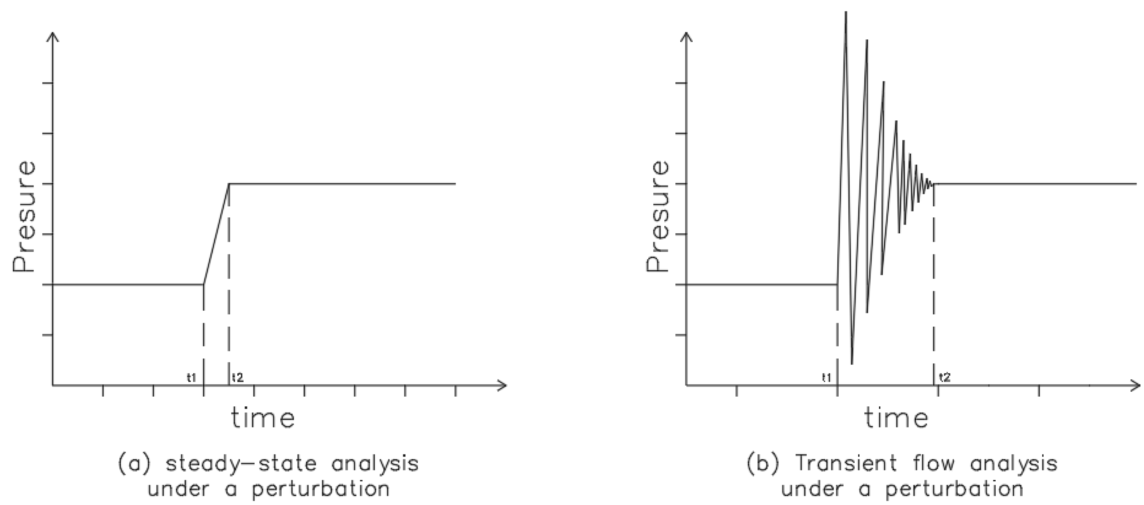


Figure 1.2 Comparison between steady-state and transient analysis

From an engineering perspective, neglecting transient hydraulic phenomena may lead to an underestimation of the mechanical stresses experienced by water distribution infrastructure. Excessive overpressures may increase the likelihood of pipe failures and damage hydraulic equipment, whereas sub-atmospheric pressures may promote column separation, cavitation, or the intrusion of contaminants into the network through existing leaks or defects. [4] Therefore, understanding the hydraulic response of a system during transient events is essential for ensuring both operational reliability and long-term infrastructure integrity.

1.4 Research Objectives

The primary objective of this thesis is to develop and apply a methodology for the analysis of hydraulic transient phenomena in a water distribution network subjected to valve closure events, with the purpose of evaluating the hydraulic response of the system and identifying infrastructure components that may be vulnerable to transient-induced pressure variations.

To achieve this objective, the following specific objectives are addressed:

- To develop a hydraulic model of the selected water distribution network under representative steady-state operating conditions.
- To simulate hydraulic transient events generated by valve closure operations using the Method of Characteristics implemented in TSNet.
- To evaluate the influence of different valve closure rules and demand conditions on the transient hydraulic response of the network.
- To estimate the mechanical response of pipelines through the calculation of hoop stresses associated with transient pressure variations and compare these stresses with representative material resistance parameters.
- To identify and spatially represent vulnerable sections of the water distribution network through the development of thematic maps that support infrastructure assessment and decision-making.

The methodology presented in this work is specifically applied to the selected case study; however, its general framework is intended to be transferable to other water distribution systems where transient flow analysis is required as part of hydraulic infrastructure evaluation and management.

1.5 Thesis Structure

This thesis is structured into six chapters that progressively develop the theoretical background, methodology, application, and analysis required to investigate hydraulic transient phenomena in a real water distribution network.

Following this introductory chapter, Chapter 2 presents the theoretical foundations of transient flow in pressurized pipe systems. The chapter discusses the physical mechanisms responsible for hydraulic transients, the propagation of pressure waves, the factors influencing transient response, and the principal numerical approaches used for transient flow modelling, with particular emphasis on the Method of Characteristics.

Chapter 3 introduces the selected case study by describing the water distribution network, its hydraulic characteristics, the available data, and the operational conditions considered throughout the investigation. The transient event analyzed in this research and the variables included in the study are also presented.

Chapter 4 describes the proposed methodology. This chapter explains the development of the hydraulic model, the selection of the analyzed valve closure scenarios, the implementation of transient simulations using TSNet, and the procedure adopted for evaluating pipe vulnerability through transient pressure analysis and hoop stress estimation.

Chapter 5 presents and discusses the results obtained from the transient simulations. The hydraulic response of the network is analyzed under different operational scenarios, and the influence of valve closure characteristics and demand conditions is evaluated. The vulnerability assessment is complemented by spatial analyses that identify the most critical sections of the network.

Finally, Chapter 6 summarizes the principal findings of the research, discusses the practical implications of the proposed methodology, identifies the main limitations of the study, and presents recommendations for future research on hydraulic transient analysis in water distribution systems.

2 Theoretical Background on Hydraulic Transients in Water Distribution Systems

Hydraulic transients are dynamic phenomena that occur whenever the equilibrium conditions of a pressurized pipe system are disturbed. Unlike steady-state analyses, which describe only the hydraulic conditions before and after a disturbance, transient flow analysis investigates the continuous evolution of pressure and flow as the system adjusts toward a new equilibrium state [4]. During this transition, pressure waves propagate throughout the pipeline network, producing hydraulic responses that may differ significantly from those predicted under steady-state assumptions.

The magnitude and characteristics of hydraulic transients depend on both the nature of the disturbance and the hydraulic properties of the system. Operational events such as valve maneuvers, pump start-ups or shutdowns, power failures, and rapid demand variations may generate pressure waves capable of producing excessive overpressures or sub-atmospheric pressures [4]. Hence, transient flow analysis plays a fundamental role in the design, operation, and protection of modern water distribution systems.

This chapter presents the theoretical principles governing hydraulic transients in pressurized pipelines. The discussion begins by distinguishing transient flow from steady-state conditions and describing the physical mechanisms responsible for pressure wave generation. Subsequently, the governing equations of transient flow, the factors influencing transient response, and the principal numerical solution techniques are introduced, with particular emphasis on the Method of Characteristics, which constitutes the numerical foundation of the simulations performed in this research.

2.1 Steady-State and Transient Flow Conditions

Steady-state and transient flow represent two fundamentally different approaches for describing the hydraulic behavior of pressurized pipe systems. Understanding the distinction between these flow conditions is essential before introducing the mechanisms responsible for hydraulic transients and the numerical methods used for their analysis.

Under steady-state conditions, the hydraulic variables at any given location within the system remain constant with time. Consequently, parameters such as pressure, flow rate, velocity, and hydraulic head do not vary while the operating conditions remain unchanged. Although turbulent fluctuations exist at very small temporal scales, engineering analyses generally consider the time-averaged hydraulic variables to be constant, allowing the system to be represented as being in hydraulic equilibrium. [4]

In contrast, unsteady flow occurs whenever one or more hydraulic variables change with time. Among the different forms of unsteady flow, transient flow specifically refers to the intermediate hydraulic condition during which a system evolves from one steady-state operating condition to another following a disturbance. Rather than occurring instantaneously, as illustrated in **Figure 1.2** this transition develops over a finite period during which pressure and flow continuously vary throughout the pipeline system. [4]

From an engineering perspective, steady-state analysis is generally sufficient for the design and operation of water distribution systems under normal operating conditions. However, when rapid operational changes occur, the assumption of hydraulic equilibrium is no longer valid. Under these circumstances, the temporal evolution of pressure and flow must be considered explicitly to accurately describe the behavior of the system and evaluate the potential risks associated with transient events.

The transition between steady-state conditions is characterized by the generation and propagation of pressure waves that travel throughout the hydraulic system. Understanding the physical mechanisms governing these pressure waves constitutes the basis of transient flow analysis and is discussed in the following section.

2.2 Origin and Causes of Transient Flows

Hydraulic transients originate whenever the hydraulic equilibrium of a pressurized system is disturbed by a change in its operating conditions. Any event that modifies the flow velocity or the boundary conditions of the pipeline initiates a transient process during which the hydraulic variables continuously adjust until a new equilibrium state is reached. [4]

The magnitude of a hydraulic transient depends primarily on the characteristics of the disturbance. Rapid changes generally produce larger pressure variations than gradual operations because the fluid has less time to adapt to the new operating conditions. Consequently, both the intensity of the disturbance and the rate at which it occurs play a fundamental role in determining the severity of the transient response. [4]

Several operational events are capable of generating hydraulic transients in pressurized systems. Among the most common are the rapid closure or opening of valves, pump start-up and shutdown operations, sudden power failures, abrupt variations in consumer demand, filling or emptying of pipelines, and accidental pipe failures. [4] Although these events differ in their physical origin, they all modify the momentum of the flowing water and initiate pressure waves that propagate throughout the hydraulic system.

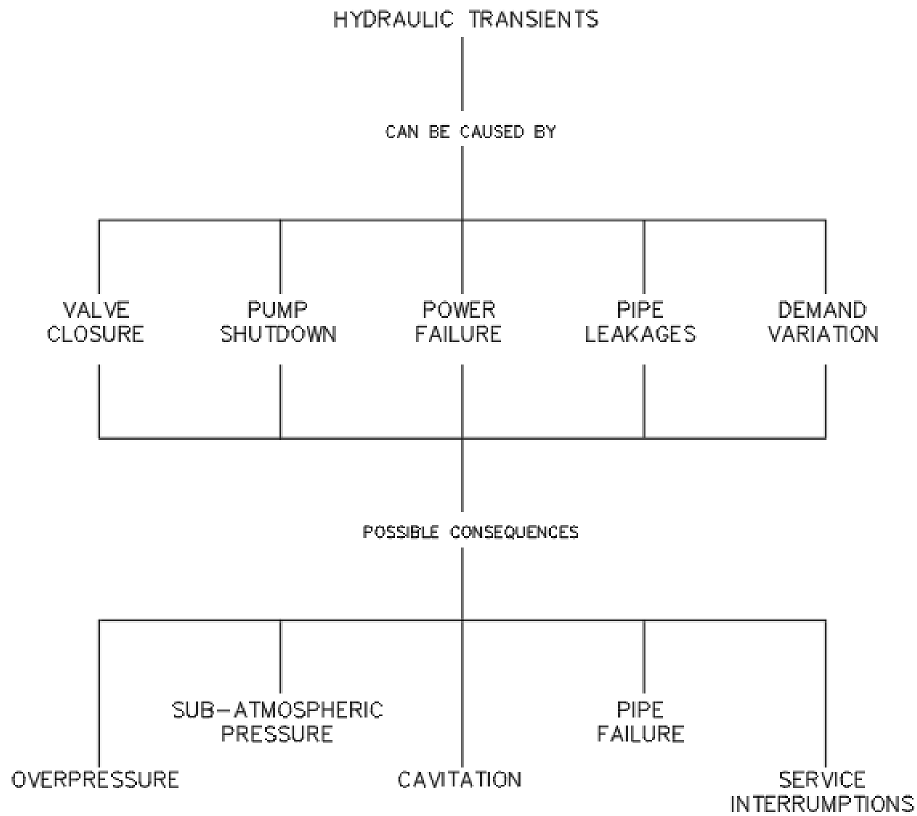


Figure 2.1 Transients causes and consequences scheme

The response of a hydraulic system to these disturbances is influenced by numerous factors, including pipe length, diameter, wall material, wave speed, operating pressure, flow velocity, and the characteristics of hydraulic control devices such as valves, pumps, air valves, and storage tanks. [4] The interaction among these parameters determines both the magnitude of the pressure fluctuations and the duration of the transient event.

In water distribution networks, operational transients are unavoidable due to the continuous changes associated with system operation. Daily demand fluctuations, maintenance activities, valve maneuvers, and unexpected operational incidents may all generate transient events of varying intensity. While many of these pressure fluctuations remain within acceptable limits, severe transients can compromise service reliability and accelerate the deterioration of hydraulic infrastructure. [4] Therefore, identifying the causes of hydraulic transients represents the first step toward developing effective protection strategies and improving the resilience of water distribution systems.

The physical mechanism by which these disturbances propagate throughout the system is explained in the following section, where the generation and propagation of pressure waves are introduced.

2.3 Pressure Wave Propagation

When a hydraulic disturbance occurs in a pressurized pipeline, the resulting changes in pressure and flow are not transmitted instantaneously throughout the system. Instead, the disturbance generates a pressure wave that propagates along the pipeline at a finite velocity, commonly referred to as the **wave speed** or **celerity**. [4] This wave carries information about the change in hydraulic conditions from the point where the disturbance originated to the remainder of the system.

To illustrate this process, consider the rapid closure of a downstream valve in a pipeline operating under steady-state conditions. Before the valve begins to close, water flows through the pipeline with a constant velocity, and the pressure distribution remains stable. As the valve movement restricts the flow area, the water immediately upstream of the valve is forced to decelerate. Since the fluid possesses inertia and cannot stop instantaneously, the kinetic energy of the moving water is converted into elastic energy through a temporary increase in pressure. This localized pressure increase constitutes the origin of the pressure wave. [4]

Once generated, the pressure wave propagates upstream through the pipeline. Consequently, it is important to distinguish between the propagation velocity of the pressure wave and the velocity of the flowing water. The pressure wave may travel at several hundred or even more than one thousand meters per second, whereas the average flow velocity in water distribution systems is typically of couple of meters per second. The wave therefore represents the transmission of pressure information rather than the physical transport of water at the same speed. [4]

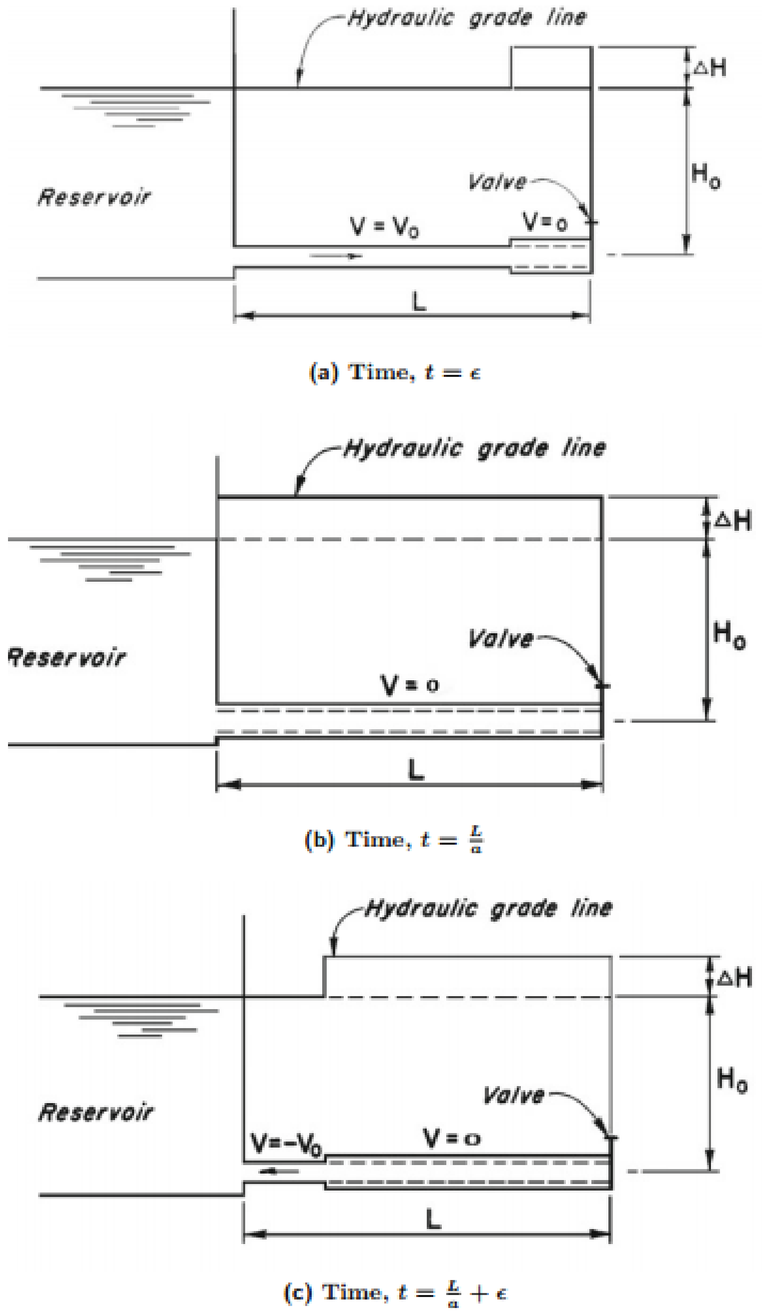


Figure 2.2 Pressure wave propagation and reflection. From Chaudhry (2014)

As the pressure wave encounters hydraulic boundaries such as reservoirs, closed valves, pipe junctions, or changes in pipe characteristics, part of the wave energy may be reflected while another portion may continue propagating through the system. [4] The interaction between incident and reflected waves produces the complex pressure fluctuations observed during transient events, particularly in branched water distribution networks where multiple reflections occur simultaneously.

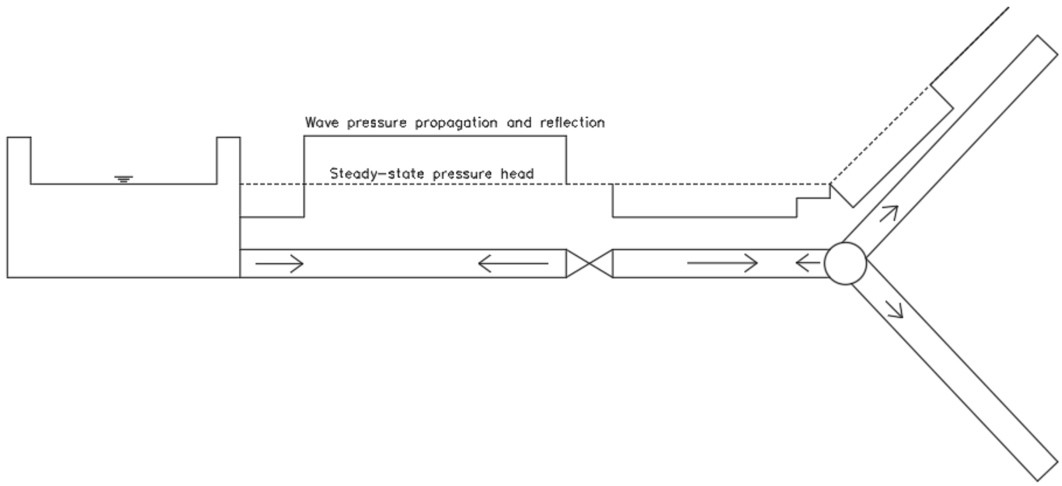


Figure 2.3 Simplified branched network wave propagation

In practical water distribution systems, these pressure waves propagate throughout the network within a relatively short period of time, allowing a disturbance produced at a single location to influence hydraulic conditions at distant points. [4] Consequently, the effects of local operational events, such as the closure of a single valve, cannot be considered purely local phenomena. Instead, the transient response depends on the hydraulic characteristics of the entire network, including its topology, pipe properties, and boundary conditions. This network-wide interaction constitutes one of the principal reasons why transient analyses are essential for evaluating the hydraulic reliability and structural safety of water distribution systems.

The propagation of pressure waves forms the physical basis of hydraulic transient analysis. To describe these phenomena quantitatively, the governing equations expressing the conservation of mass and momentum under transient conditions are introduced in the following section.

2.4 Governing Equations of Transient Flow

The propagation of hydraulic transients in pressurized pipelines is governed by the fundamental principles of conservation of mass and conservation of momentum. Unlike steady-state flow, where hydraulic variables are assumed to remain constant with time, transient flow requires both spatial and temporal variations of pressure and flow rate to be considered simultaneously. [4] Therefore, the hydraulic behavior of the system is described by a set of coupled partial differential equations that relate changes in discharge and hydraulic head as functions of both distance and time.

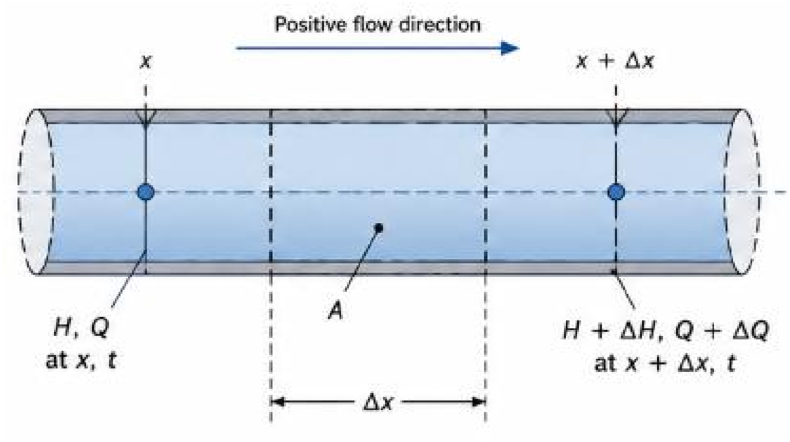


Figure 2.4 Differential control volume of a pipe element.

The first governing equation expresses the conservation of mass, also referred to as the continuity equation(2.1). During transient conditions, any local variation in flow rate produces a corresponding variation in pressure due to the compressibility of the fluid and the elasticity of the pipe wall. Thus, the continuity equation establishes the relationship between temporal changes in hydraulic head and spatial variations in discharge. [4]

The second governing equation is obtained from the conservation of linear momentum(2.2). This equation accounts for the balance between pressure forces, inertial effects, gravity, and frictional resistance acting on the moving fluid. Together with the continuity equation, it provides a complete mathematical description of transient flow in pressurized pipelines. [4]

For one-dimensional transient flow in an elastic pipe, the governing equations may be written in terms of hydraulic head, H, and discharge, Q, as follows.

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \qquad (2.1)$$

where:

- H= hydraulic head (m)
- Q= discharge (m³/s)
- a= pressure wave speed (m/s)
- A= pipe cross-sectional area (m²)
- g= gravitational acceleration (m/s²)

$$\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + \frac{f \cdot Q|Q|}{2DA} = 0 \qquad (2.2)$$

where:

- f represents D-W coefficient associated with friction losses.

These two equations constitute the mathematical foundation of transient flow analysis. Because they are nonlinear, hyperbolic partial differential equations, analytical solutions are only possible for highly simplified cases. Real water distribution systems contain numerous pipes, junctions, valves, reservoirs, and other hydraulic components, making analytical solutions impractical. Numerical techniques are required to solve the governing equations efficiently under realistic operating conditions. [4]

Among the different numerical approaches developed for this purpose, the Method of Characteristics has become one of the most widely adopted techniques due to its numerical stability and accuracy in modelling pressure wave propagation. Before introducing this method, it is first necessary to examine one of the most important parameters governing transient behavior: the wave propagation speed.

2.5 Wave Speed

The speed at which a pressure wave propagates through a pressurized pipeline is one of the most influential parameters governing hydraulic transient behavior. Commonly referred to as **wave speed** or **celerity**, this parameter determines how rapid pressure disturbances travel throughout the system and directly affects both the magnitude and timing of transient pressure fluctuations. [4] Consequently, an accurate estimation of wave speed is essential for realistic transient flow modelling.

If both the fluid and the pipe walls were perfectly rigid, the propagation velocity would depend solely on the compressibility of the fluid. However, in real WDNs the pipe walls deform elastically under pressure. Part of the pressure energy is therefore absorbed by the radial expansion of the pipe, reducing the speed at which the pressure wave propagates. This interaction between the compressibility of water and the elasticity of the pipe wall leads to the well-known **Korteweg equation (2.3)**, which provides a more realistic estimate of wave speed in elastic pipelines. [4]

$$a = \sqrt{\frac{\frac{K}{\rho}}{1 + \frac{KD}{Ee}}} \tag{2.3}$$

Where:

a = wave speed (m/s)

K = bulk modulus of elasticity of water

ρ = water density

D = internal pipe diameter

E = Young's modulus of the pipe material

e = pipe's wall thickness

The previous expression demonstrates that wave speed is not a unique property of water but rather a combined characteristic of both the fluid and the pipeline. Consequently, different pipe materials exhibit significantly different wave propagation velocities. [4] Metallic pipes, such as steel or ductile iron, generally present high wave speeds because of their greater structural stiffness, whereas thermoplastic materials such as PVC and HDPE produce considerably lower values due to their higher deformability.

Since wave speed directly influences the hydraulic response of a system during transient events, realistic values should be assigned to each pipe material when performing numerical simulations. In this research, wave speed values were selected according to the material characteristics of the analyzed water distribution network and incorporated into the transient model developed in TSNet. The adopted values are presented in Chapter 4 together with the modelling methodology.

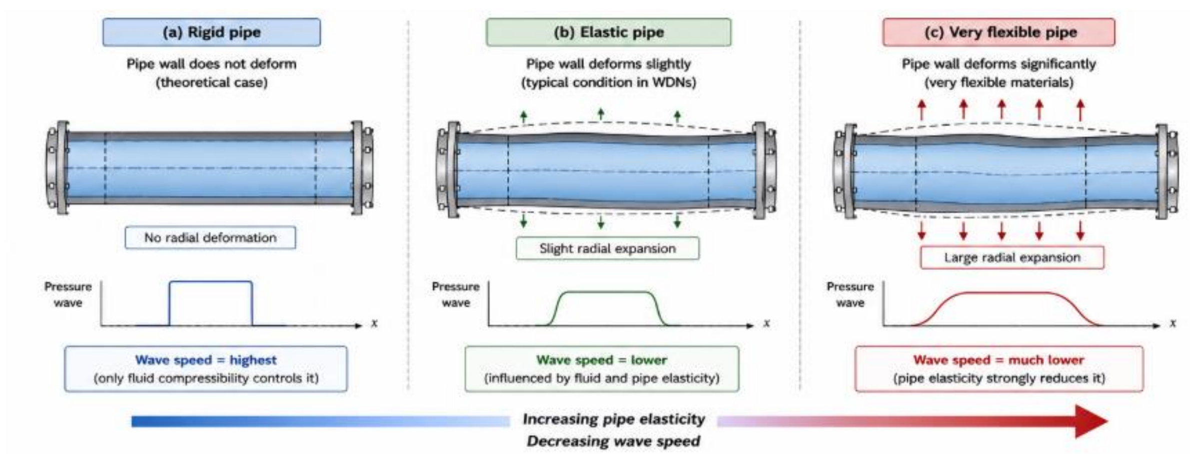


Figure 2.5 Influence of pipe elasticity on wave speed.

2.6 Numerical Approaches for Transient Flow Analysis

The governing equations of transient flow presented in the previous section consist of a system of coupled, nonlinear, hyperbolic partial differential equations. Although analytical solutions exist for a limited number of highly simplified problems, real water distribution systems contain numerous pipes, junctions, reservoirs, pumps, valves, and other hydraulic components that make analytical solutions impractical. Consequently, numerical methods are required to obtain accurate solutions for transient flow in realistic hydraulic networks. [4]

Over the past decades, several numerical techniques have been developed to solve the governing equations of hydraulic transients. These include finite difference methods, finite element methods, finite volume methods, and the Method of Characteristics (MOC). Each approach transforms the governing partial differential equations into a system of algebraic equations that can be solved iteratively while satisfying the hydraulic boundary conditions of the system.

Among these numerical approaches, the Method of Characteristics has become the most widely adopted technique for modelling hydraulic transients in pressurized pipe systems. Its popularity is primarily due to its numerical stability, computational efficiency, and ability to accurately reproduce the propagation and reflection of pressure waves under a wide range of operating conditions. Consequently, the Method of Characteristics has been implemented in numerous commercial and research-oriented transient simulation tools. [4]

In the present research, transient simulations were performed using **TSNet**, an open-source software package specifically developed for transient analysis in water distribution networks. TSNet employs the Method of Characteristics to solve the transient flow equations throughout the network while accounting for the hydraulic interactions among pipes, junctions, reservoirs, tanks, valves, and other hydraulic components. [5] A detailed description of the Method of Characteristics, which constitutes the numerical foundation of TSNet, is presented in the following section.

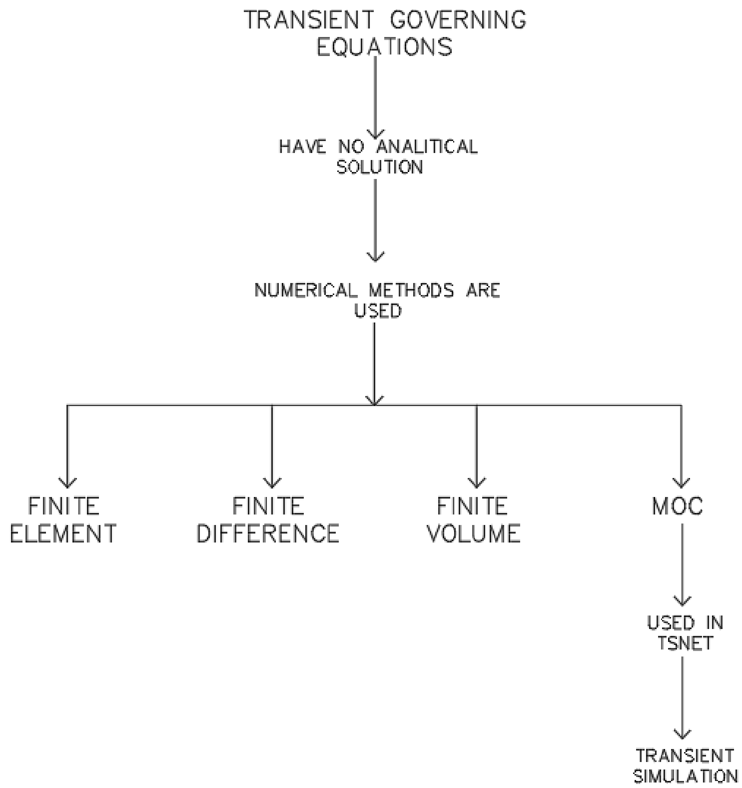


Figure 2.6 Flowchart of implemented Transient simulation

2.7 Method of Characteristics

The Method of Characteristics is based on the transformation of the transient flow governing equations into a set of ordinary differential equations that can be solved along specific paths, known as **characteristic lines**, in the space-time domain. [4]

Unlike conventional finite difference approaches, the Method of Characteristics follows the physical propagation of pressure waves through the pipeline. Rather than solving the equations independently at fixed spatial locations, the method computes the hydraulic conditions along trajectories that coincide with the propagation of hydraulic information. As a result, it provides an accurate representation of wave travel, reflection, and interaction within complex hydraulic systems. [4]

The characteristic lines correspond to the paths followed by pressure disturbances as they travel through the pipeline at wave speed. Two families of characteristics are defined, representing waves propagating in opposite directions. These are commonly denoted as the positive characteristic, C^{+}, and the negative characteristic, C^{-}, corresponding to waves travelling downstream and upstream, respectively. [4] Along each characteristic line, the original partial differential equations reduce to ordinary differential equations that relate hydraulic head and discharge.

For one-dimensional transient flow, the governing equations may therefore be expressed along the characteristic lines as

$$C^{+}: dH + \frac{a}{gA}\, dQ + h_f = 0 \tag{2.4}$$

$$C^{-}: dH - \frac{a}{gA}\, dQ + h_f = 0 \tag{2.5}$$

where $h_f$represents the friction term evaluated over the computational interval. [4]

These characteristic equations constitute the basis of the numerical algorithm. The hydraulic variables are calculated sequentially at discrete computational points by combining information obtained from neighboring points at the previous time step. Consequently, the complete transient response of the hydraulic system can be obtained by repeatedly advancing the numerical solution through time while satisfying the corresponding boundary conditions at reservoirs, tanks, valves, pumps, and pipe junctions. [4]

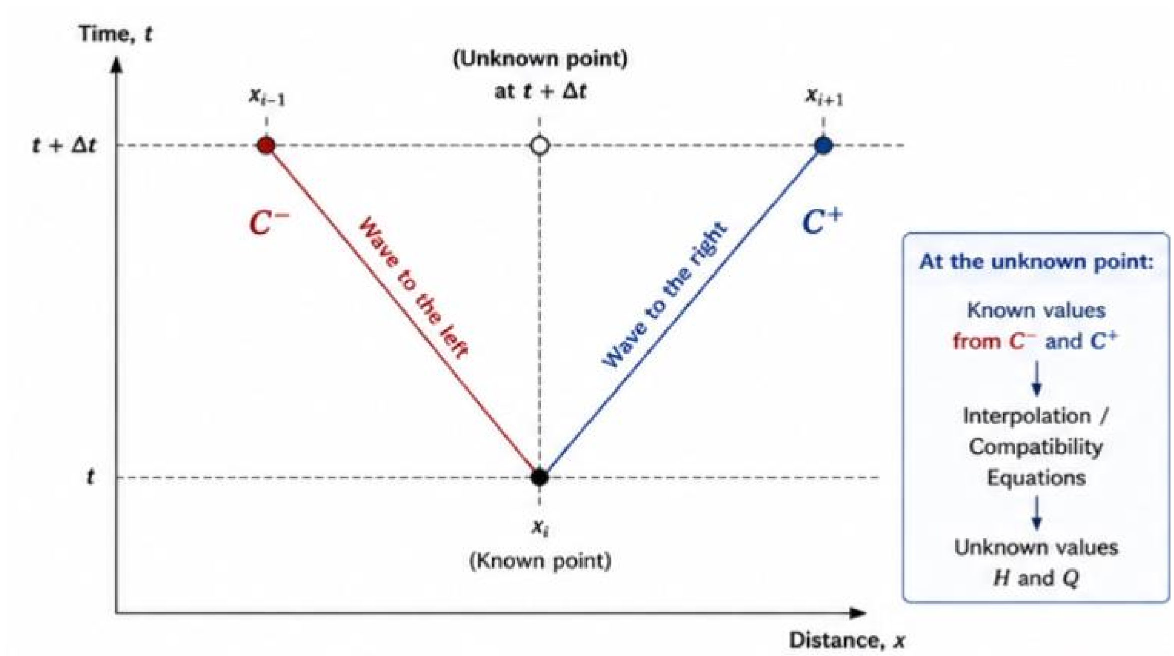


Figure 2.7 Characteristic lines in x-t plane. adapted from Chaudhry (2014)

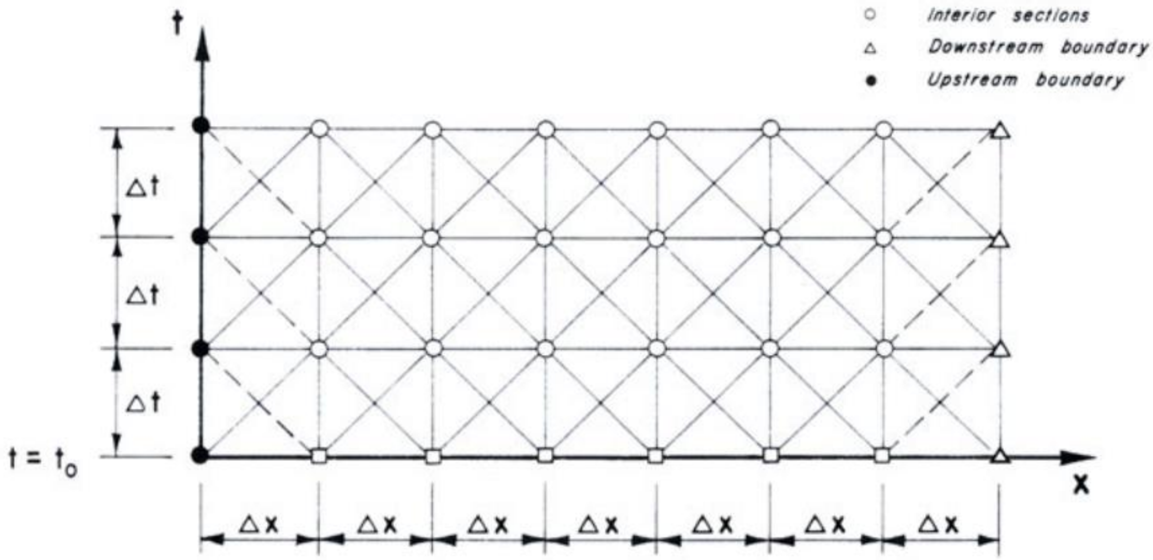


Figure 2.8 Characteristic grid. From Chaudhry (2014)

The widespread adoption of the Method of Characteristics is primarily attributed to its numerical stability, physical consistency, and ability to accurately reproduce the propagation and reflection of pressure waves in pressurized pipe systems. Owing to these advantages, the method has become the standard numerical approach implemented in many transient simulation programs used in both research and engineering practice. [4]

3 Case Study: Water Distribution Network Description

The theoretical background presented in the previous chapter provides the basis for understanding and modelling hydraulic transients in pressurized pipe systems. However, the application of these concepts to a real water distribution network requires a clear description of the system under investigation, the available data, and the operating conditions analyzed.

The case study considered in this research corresponds to a real urban water distribution network located in a major Colombian city. The hydraulic model and associated operational data were provided for academic research purposes. In accordance with confidentiality requirements, specific information that could identify the water utility or the exact location of the network has been omitted or anonymized. This anonymization does not affect the methodological development or the interpretation of the hydraulic results presented in this thesis.

This chapter introduces the analyzed water distribution network, hereafter referred to as the study network. First, the general characteristics of the system are described, including its main hydraulic and topological features. Subsequently, the available data used to develop the hydraulic model is presented. Finally, the transient event considered in this research is introduced, establishing the basis for the methodology described in the following chapter.

3.1 Description of the Analyzed Network

The study network considered in this research corresponds to a real urban water distribution system serving a densely populated sector of a major Colombian city. The system forms part of the municipal drinking water supply infrastructure and operates as a pressurized distribution network designed to deliver potable water to residential, commercial, and public consumers. The hydraulic characteristics of the analyzed system are representative of medium-to-large urban water distribution networks commonly found in Colombia.

The study area is located in a tropical region characterized by relatively stable temperatures throughout the year and a moderate average elevation above sea level. These climatic conditions result in a continuous demand for potable water without significant seasonal variations associated with freezing temperatures or snowmelt. Consequently, the hydraulic operation of the distribution network is primarily influenced by the temporal variation of consumer demand rather than by extreme climatic conditions.

The analyzed network comprises a complex arrangement of transmission and distribution pipelines interconnected through junctions and control valves. Water is supplied from a single upstream source and distributed throughout the study area via a branched and partially looped pipe system. The network contains pipes of different diameters, materials, and installation periods, reflecting the gradual expansion and rehabilitation processes typically observed in urban water distribution systems.

The hydraulic model available for this research was developed using EPANET and includes all the information required to perform both steady-state and transient analyses. The model incorporates the geometric characteristics of the network, including pipe lengths, diameters, elevations, roughness coefficients, nodal demands, and the location of hydraulic control elements. This information provides a reliable representation of the physical system and constitutes the basis for the transient simulations performed in this investigation.

A summary of the principal characteristics of the study network is presented in **Table 3-1**, while the overall layout of the hydraulic model is illustrated in **Figure 3.1**.

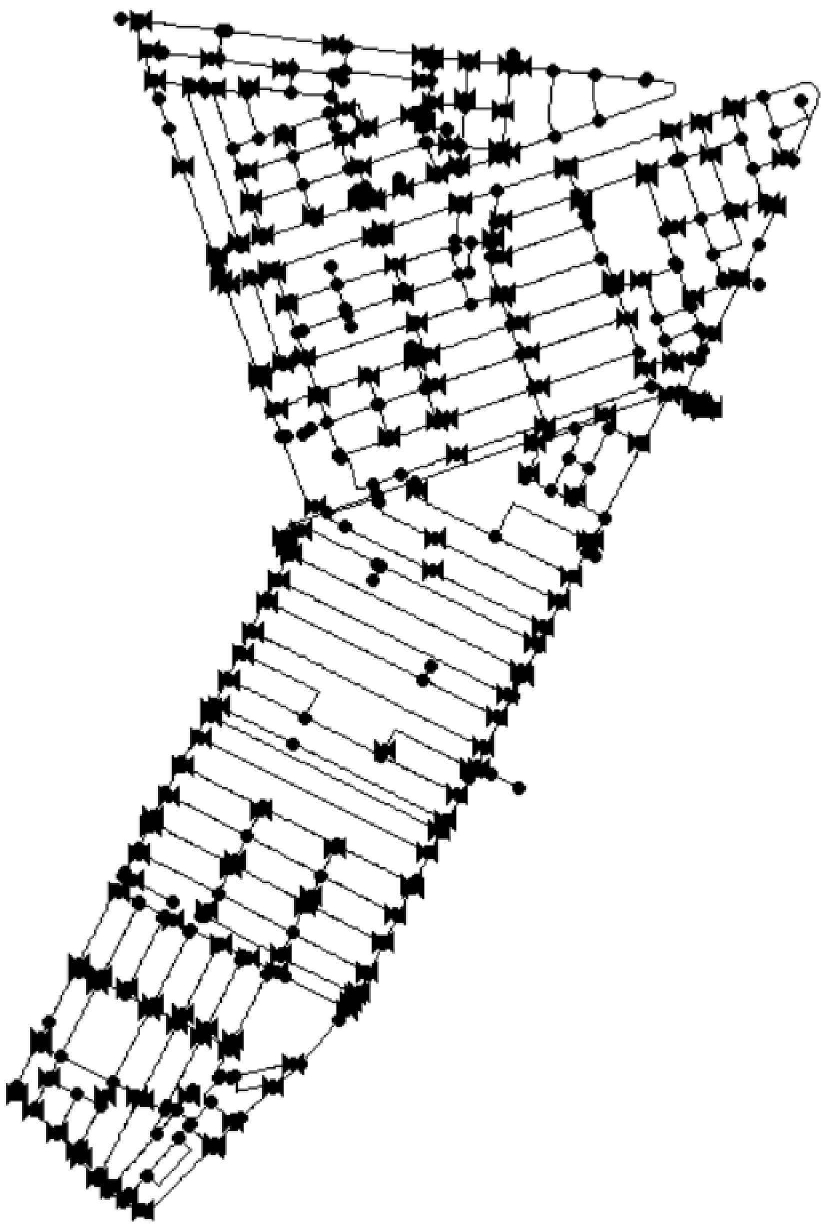


Figure 3.1 General Layout of the analyzed WDN

Table 3-1Topological parameters of the studied WDN

PARAMETER	VALUE
TOTAL NUMBER OF PIPES	771
TOTAL NUMBER OF JUNCTIONS	864
TOTAL NUMBER OF VALVES	214
TOTAL PIPE LENGHT	35.9 Km
PIPE DIAMETER RANGE	75-600 mm
PIPE MATERIALS	DI, CI, CCP, ST, AC, PVC, PAD

3.2 Available Data and Hydraulic Model

The development of a reliable transient model requires accurate information describing both the physical characteristics of the water distribution system and its hydraulic operation. For this research, a comprehensive dataset was available, including a previously calibrated hydraulic model together with the physical and operational information necessary to perform both steady-state and transient analyses.

The primary source of information consisted of a calibrated hydraulic model developed in EPANET provided for academic research purposes. The model had previously been calibrated to reproduce the hydraulic behavior of the real distribution system under normal operating conditions, providing a reliable representation of the network prior to the transient analysis. The availability of a calibrated model constitutes a significant advantage, as it ensures that the initial hydraulic conditions used for the transient simulations accurately represent the real operating state of the system.

The EPANET model contained the complete hydraulic description of the network, including the connectivity between hydraulic elements, pipe lengths and diameters, junction elevations, roughness coefficients, base demands, temporal demand patterns, and the location of the principal hydraulic control elements. This information was used to reproduce the steady-state hydraulic conditions from which all transient simulations were initiated.

In addition to the hydraulic information, detailed physical characteristics of each pipeline were available. These included the construction material associated with every pipe, allowing the assignment of representative mechanical properties required for transient modelling. Since the propagation of pressure waves depends on both the compressibility of water and the mechanical behavior of the pipe wall, the availability of pipe material information was particularly important for assigning appropriate wave speed values throughout the network. Furthermore, these data were later used to evaluate the structural response of the pipelines through the calculation of circumferential (hoop) stresses generated during transient events.

The available information also included the operational configuration of the network, making it possible to reproduce different demand conditions and operating scenarios. These steady-state operating conditions served as the initial state for every transient simulation performed in this research, ensuring consistency between the hydraulic model and the transient analyses.

Table 3-2 summarizes the principal categories of information available for the development of the transient model.

Table 3-2 Available information for the development of the model

Information Category	Description	Application in the research
Network topology	Connectivity between hydraulic elements	Hydraulic model construction
Pipe geometry	Length and internal diameter	Hydraulic calculations and transient simulations

Pipe material	Construction material of each pipe	Wave speed assignment and structural assessment
Hydraulic roughness	Pipe roughness coefficients	Steady-state simulations
Junction elevations	Ground elevations	Pressure calculations
Water demand	Base demands and demand patterns	Definition of operating conditions
Hydraulic controls	Reservoirs, valves and other control elements	Boundary conditions for the hydraulic model

The combination of a calibrated hydraulic model and detailed information describing the physical characteristics of the network provided a robust foundation for the transient analyses presented in this thesis. While the EPANET model supplied the hydraulic conditions required to initialize every simulation, the complementary information regarding pipe geometry and materials enabled a realistic representation of pressure wave propagation and the subsequent structural assessment of the pipeline system.

3.3 Selected Transient Event

Hydraulic transients may be generated by a wide variety of operational events as explained previously on **Section 2.2** Among these mechanisms, valve closure represents one of the most common operational events capable of producing significant pressure fluctuations in water distribution systems. The rapid reduction of flow velocity caused by a valve maneuvers generate pressure waves that propagate throughout the network, potentially affecting hydraulic conditions far from the location where the operation takes place.

From an operational perspective, valve closures occur during routine maintenance activities, emergency interventions, network isolation procedures, and operational reconfigurations. Although these maneuvers are generally performed under controlled conditions, inappropriate closure rates or unfavorable hydraulic operating conditions may produce considerable transient pressures capable of affecting both the hydraulic performance and the structural integrity of the distribution system.

The present research focuses on the transient response generated by valve closure events because they represent a realistic operational scenario while also providing an effective framework for evaluating the propagation of pressure waves throughout complex water distribution networks. Unlike localized steady-state analyses, transient events allow the dynamic interaction between different sectors of the network to be investigated, highlighting how a disturbance generated at a single location may influence hydraulic conditions across the entire system.

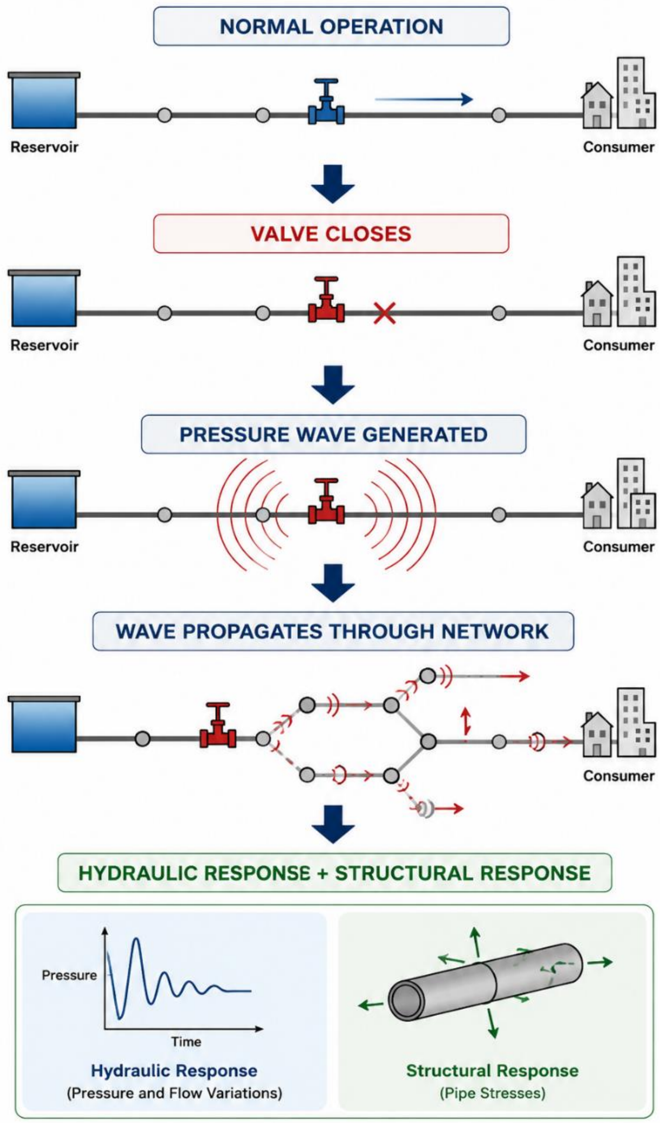


Figure 3.2 Conceptual representation of the hydraulic response to a valve closure event in a water distribution network.

The objective of analyzing valve closure events is therefore not limited to evaluating the hydraulic response immediately upstream or downstream of the operated valve. Instead, the transient analysis aims to identify how pressure waves propagate through the network, determine the spatial distribution of pressure variations, and evaluate the corresponding structural response of the pipelines. This approach provides valuable information regarding the vulnerability of different sectors of the network under representative operational disturbances.

3.4 Operational Conditions Considered

The objective of the present research is to evaluate the hydraulic and structural response of a real water distribution network subjected to transient events generated by valve closure operations. Unlike conventional steady-state analyses, which describe only the initial and final operating conditions of the system, the transient approach adopted in this work investigates the dynamic evolution of pressure and flow throughout the entire network during the transition between equilibrium states.

The analysis focuses on identifying the pressure fluctuations generated by representative valve closure events and evaluating their spatial distribution across the network. Attention is given to the occurrence of maximum overpressures and minimum pressures, since these variables are directly related to the hydraulic performance of the system and may compromise the integrity of hydraulic infrastructure under severe operating conditions.

In addition to the hydraulic response, this research incorporates a structural assessment of the pipeline system by evaluating the circumferential (hoop) stresses induced by transient pressures. These stresses are calculated for every pipeline in the network using the maximum transient pressures obtained from the numerical simulations and are subsequently compared with representative allowable and resistant stresses associated with each pipe material. This approach makes it possible to identify those sectors of the network that are more susceptible to structural damage during transient events.

Finally, the results obtained from the transient simulations and the structural assessment are integrated within a geographic information system (GIS) environment to produce spatial vulnerability maps. These maps provide a comprehensive visualization of the distribution of hydraulic and structural risk throughout the network, facilitating the identification of critical sectors and supporting future decision-making regarding network operation, maintenance, and rehabilitation.

The framework presented in this chapter establishes the basis for the transient modelling methodology developed in this research. The following chapter describes the numerical implementation of the hydraulic model, the selection of the analyzed scenarios, and the procedures adopted to evaluate both the hydraulic and structural response of the study network.

4 Methodology

The methodology adopted in this research is summarized in **Figure 4.1**. The workflow illustrates the sequence of analyses performed, from the preparation of the calibrated hydraulic model to the final vulnerability assessment of the water distribution network. Each stage of the methodology is described in detail in the following sections.

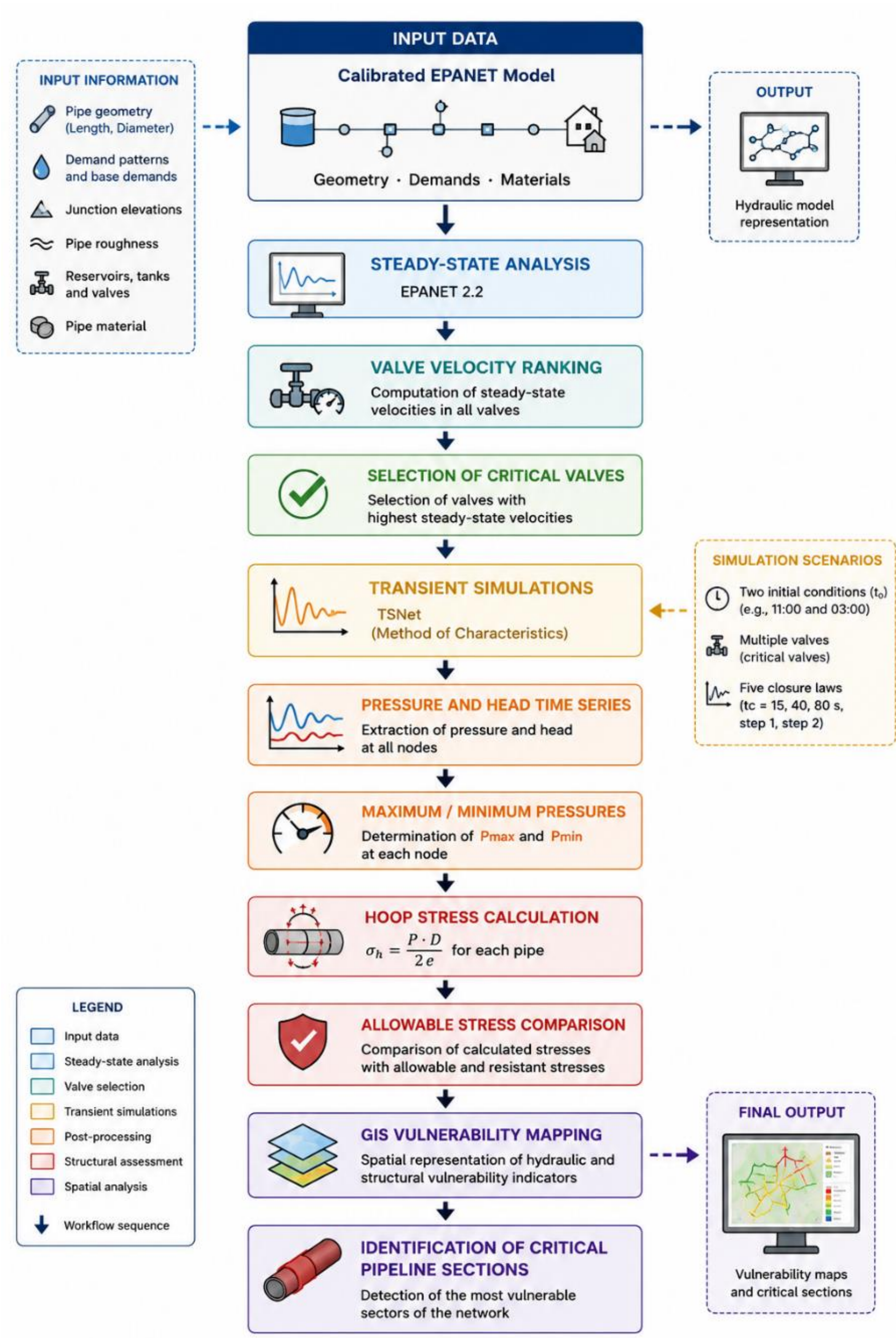


Figure 4.1 Workflow of the hydraulic analysis

4.1 Hydraulic Model Preparation

The transient modelling process was based on the calibrated EPANET hydraulic model described in Chapter **3**. Since the original model had been developed for steady-state hydraulic analyses, several preparation steps were required before performing transient simulations. These steps ensured that the hydraulic model contained all the information necessary to accurately reproduce the dynamic behavior of the water distribution network under transient conditions.

The first stage consisted of verifying the integrity of the hydraulic model and its compatibility with the numerical tools employed in this research. The network topology, hydraulic elements, boundary conditions, and pipe attributes were reviewed to confirm that the model could be successfully imported into the transient simulation environment without altering its hydraulic characteristics.

Particular attention was given to the physical information associated with each pipeline. Geometric properties such as length and diameter, together with hydraulic parameters including roughness coefficients, were verified to ensure consistency throughout the network. Additionally, the construction material assigned to each pipe was reviewed because this information was subsequently used to define representative wave speed values during the transient simulations and to evaluate the structural response of the pipeline system.

Following the verification process, the hydraulic model was imported into the transient simulation framework while preserving the original hydraulic configuration. The calibrated steady-state behavior of the network therefore constituted the starting point for all subsequent analyses presented in this research.

The preparation of the hydraulic model provided the foundation for the steady-state simulations described in the following section, where the initial operating conditions adopted for the transient analyses were established.

4.2 Initial Steady-State Simulation

The first stage of the transient analysis consisted of establishing the initial steady-state hydraulic conditions of the study network. As discussed in Chapter **2.2**, every hydraulic transient originates from a previously existing equilibrium state. Consequently, the accuracy of the transient simulations depends directly on the correct representation of the hydraulic conditions immediately before the disturbance occurs.

The steady-state simulation was performed using EPANET 2.2, employing the calibrated hydraulic model described in the previous chapter. The software was used to compute the hydraulic conditions throughout the network under a total time simulation of 24 hours, with a specific demand pattern along the entire simulation that represents the typical demand along the day, providing the initial values of pressure, hydraulic head, flow rate, and flow velocity required to initialize the transient simulations. [3]

Rather than considering a single operating condition, two representative demand scenarios were selected in order to evaluate the influence of the initial hydraulic state on the transient response of the network. The first scenario corresponds to a period of high-water demand, representing typical daytime operating conditions, while the second corresponds to a period of low demand, representative of nighttime operation. These two scenarios were selected because they produce significantly different flow distributions and hydraulic conditions, allowing the influence of the initial operating state on the propagation of transient pressure waves to be evaluated.

For each operating condition, the steady-state solution provided the hydraulic variables required to initialize the transient simulations. In particular, the flow velocities obtained in each pipeline were subsequently used to identify the valves associated with the highest operating velocities, while the computed pressures and flow rates served as the initial conditions for all transient analyses performed using TSNet.

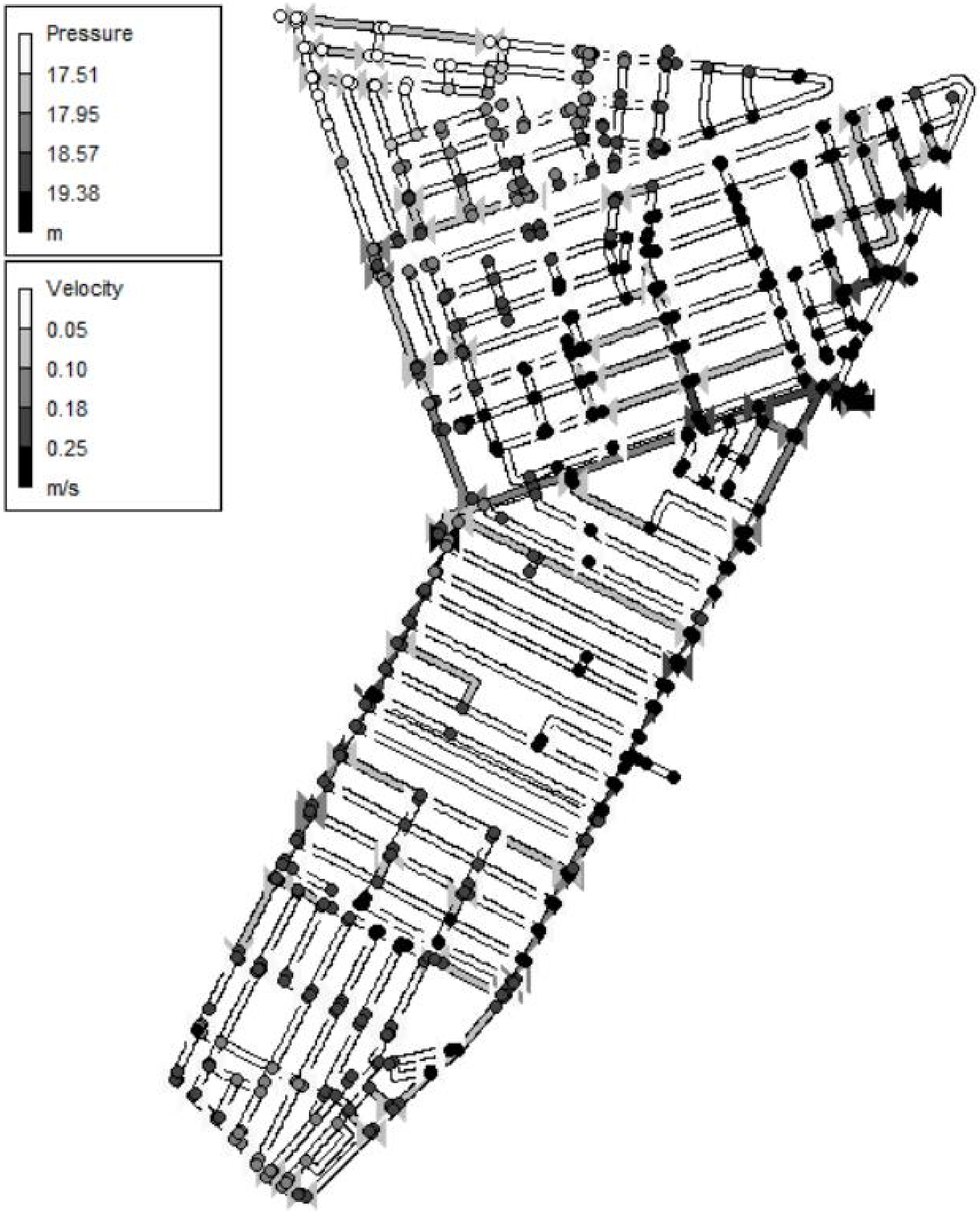


Figure 4.2 Scenario with low demand (3:00 AM)

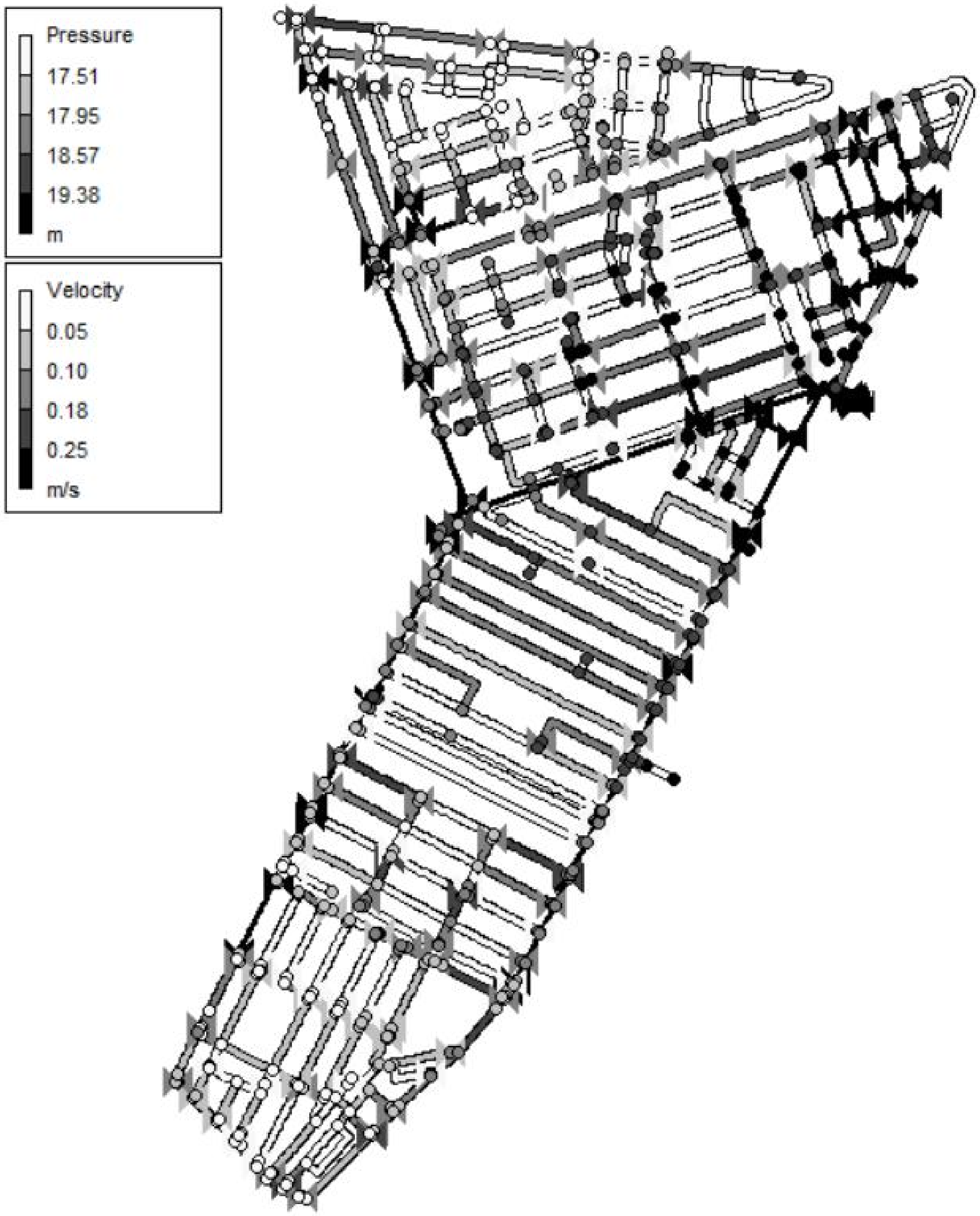


Figure 4.3 Scenario with high demand (11:00 AM)

The two steady-state operating conditions constitute the starting point for the subsequent stages of the proposed methodology. The procedure adopted to identify the most representative valve closure locations based on these hydraulic conditions is presented in the following section.

4.3 Selection of Critical Valves Based on Flow Velocity

The location at which a transient event is generated has a significant influence on the hydraulic response of a water distribution network. Consequently, the selection of representative valve closure locations constitutes a key step in the proposed methodology. Although the study network contains a considerably larger number of isolation valves, analyzing every possible valve closure would require an excessive number of transient simulations without necessarily providing additional insight into the hydraulic behavior of the system.

For this reason, a selection criterion based on the steady-state hydraulic conditions of the network was adopted. The underlying hypothesis is that valve closures occurring under higher flow velocities are more likely to generate severe transient events than closures occurring under low-flow conditions. This assumption is supported by the Joukowsky equation **(4.1)**, which establishes that the magnitude of the pressure variation generated during a rapid change in velocity is directly proportional to both the wave speed and the change in flow velocity. [4]

$$\Delta \mathrm{H} = \mathrm{a} \cdot \frac{\Delta V}{g} \tag{4.1}$$

Where:

- ΔH= change in hydraulic head (m)
- a= wave propagation speed (m/s)
- ΔV= change in flow velocity (m/s)
- g= gravitational acceleration (m/s²)

Although the transient analyses performed in this research were carried out using numerical simulations rather than the direct application of the Joukowsky equation, this relationship provides the physical justification for selecting valves associated with the highest steady-state flow velocities. Higher operating velocities generally imply larger velocity variations during valve closure and, consequently, greater potential for generating significant transient pressures.

The steady-state simulations described in the previous section were therefore used to compute the flow velocity throughout the network under the two representative operating conditions. Since the hydraulic behavior of the system changes with demand, independent velocity rankings were obtained for both the high-demand and low-demand scenarios. This procedure ensured that valves exhibiting significant hydraulic importance under different operating conditions were considered during the selection process rather than relying on a single operating state.

The valves were subsequently ranked according to the flow velocity of the associated pipeline. A total of twenty valves presenting the highest representative operating velocities were selected for the transient analyses. In a limited number of cases, valves that were not suitable for transient simulation due to modelling or operational considerations such as Boundary control valves located at the interface between the study network and adjacent distribution sector were excluded and replaced by the next highest-ranked candidates. This procedure ensured the consistency of the analyzed scenarios while maintaining the original selection criterion based on hydraulic significance.

The adopted methodology provides a practical compromise between computational efficiency and hydraulic representativeness. Instead of evaluating every valve contained in the network, the analysis concentrates on those locations with the highest probability of generating severe transient events, considerably reducing the computational effort while preserving the ability to identify the most critical hydraulic responses.

The complete list of the selected valves together with their corresponding steady-state flow velocities is presented in **Table 4-1**. These valves constitute the basis for all transient simulations performed in the subsequent stages of this research.

Table 4-1 Selected Valves by Initial Velocity

t0_label	valve_id	valve_type	initial_flow_m3s	diameter_m	velocity_ms
T0_11am	VS-21846	TCV	0.030	0.2	0.97
T0_11am	VS-10011	TCV	0.079	0.4	0.63
T0_11am	VS-9986	TCV	0.019	0.2	0.62
T0_11am	VS-13501	TCV	0.019	0.2	0.61
T0_11am	VS-10001	TCV	0.019	0.2	0.60
T0_11am	VS-19271	TCV	0.004	0.1	0.54
T0_11am	VS-9970	TCV	0.009	0.15	0.52
T0_11am	VS-24712	TCV	0.004	0.1	0.52
T0_11am	VS-9971	TCV	0.004	0.1	0.51
T0_11am	VS-23398	TCV	0.016	0.2	0.51
T0_11am	VS-9994	TCV	0.015	0.2	0.49
T0_11am	VS-11307	TCV	0.014	0.2	0.46
T0_11am	VS-11251	TCV	0.014	0.2	0.43
T0_11am	VS-11306	TCV	0.012	0.2	0.39
T0_11am	VS-9923	TCV	0.026	0.3	0.37
T0_11am	VS-24733	TCV	0.003	0.1	0.36
T0_11am	VS-12983	TCV	0.011	0.2	0.35
T0_11am	VS-21792	TCV	0.010	0.2	0.33
T0_11am	VS-21791	TCV	0.010	0.2	0.31
T0_11am	VS-23627	TCV	0.022	0.3	0.31
T0_3am	VS-21846	TCV	0.010	0.2	0.33

T0_3am	VS-10011	TCV	0.027	0.4	0.21
T0_3am	VS-9986	TCV	0.007	0.2	0.21
T0_3am	VS-13501	TCV	0.006	0.2	0.20
T0_3am	VS-10001	TCV	0.006	0.2	0.20
T0_3am	VS-19271	TCV	0.001	0.1	0.18
T0_3am	VS-9970	TCV	0.003	0.15	0.18
T0_3am	VS-24712	TCV	0.001	0.1	0.18
T0_3am	VS-9971	TCV	0.001	0.1	0.17
T0_3am	VS-23398	TCV	0.005	0.2	0.17
T0_3am	VS-9994	TCV	0.005	0.2	0.17
T0_3am	VS-11307	TCV	0.005	0.2	0.16
T0_3am	VS-11251	TCV	0.005	0.2	0.15
T0_3am	VS-11306	TCV	0.004	0.2	0.13
T0_3am	VS-9923	TCV	0.009	0.3	0.13
T0_3am	VS-24733	TCV	0.001	0.1	0.12
T0_3am	VS-12983	TCV	0.004	0.2	0.12
T0_3am	VS-21792	TCV	0.004	0.2	0.11
T0_3am	VS-21791	TCV	0.003	0.2	0.11
T0_3am	VS-23627	TCV	0.007	0.3	0.11

4.4 Transient Modelling Using TSNet

The transient analyses performed in this research were carried out using **TSNet**, an open-source Python package specifically developed for transient simulations in water distribution networks. The software extends the hydraulic capabilities of EPANET by incorporating transient flow analysis based on the Method of Characteristics, allowing the dynamic evolution of hydraulic variables to be simulated following operational disturbances such as valve closures and pump operations. [5]

Unlike conventional steady-state hydraulic simulations, transient modelling requires the temporal evolution of pressure and flow to be computed throughout the network. Consequently, every simulation performed in this research started from the steady-state hydraulic conditions established in the previous sections and subsequently evaluated the response of the network following a prescribed valve closure operation.

The transient modelling methodology adopted in this research consisted of defining the initial hydraulic conditions, selecting the valve closure law, specifying the numerical parameters required by the solver, and performing the transient simulations for every selected valve and operating scenario. The following sections describe each of these stages in detail.

4.4.1 Definition of the Initial Conditions

Every transient simulation performed in this research was initialized from a previously computed steady-state hydraulic solution. Since hydraulic transients represent the transition between two equilibrium states, the definition of realistic initial conditions is essential to ensure that the simulated pressure waves originate from representative operating conditions of the water distribution network.

As described in Section **4.2**, two steady-state operating conditions were considered to account for the variability of the hydraulic behavior associated with changes in water demand. The first condition corresponds to a representative high-demand period at **11:00**, while the second represents a low-demand period at **03:00**. These operating conditions were obtained from the calibrated EPANET model and subsequently used as the initial hydraulic time for the transient simulations, 39600s and 10800s respectively were defined as t0.

For each selected operating condition, the steady-state solution provided the initial hydraulic head, pressure, flow rate, and flow velocity throughout the entire network. These variables were directly imported into the transient model, ensuring that every simulation started from a physically consistent hydraulic equilibrium before the valve closure event was introduced.

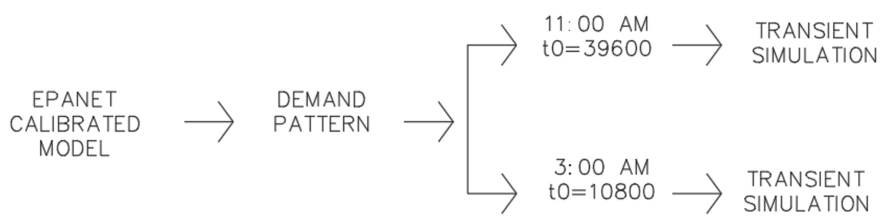


Figure 4.4 Transient Simulations t0

By considering two different initial operating conditions, the proposed methodology makes it possible to evaluate the influence of the hydraulic state of the network on the transient response. This approach allows the comparison of pressure wave propagation under significantly different flow distributions, providing a broader assessment of the hydraulic behavior of the study network.

The steady-state conditions defined in this section constituted the initial state for all transient simulations. The transient disturbance was subsequently introduced by prescribing different valve closure laws, as described in the following section.

4.4.2 Valve Closure Rules

The hydraulic response generated during a transient event depends not only on the initial operating conditions of the network but also on the temporal evolution of the valve maneuver. Although the initial and final valve positions may be identical, different closure profiles produce different rates of flow deceleration, resulting in distinct pressure wave characteristics. Consequently, the definition of the valve closure law constitutes one of the most important parameters in transient flow modelling.

To evaluate the influence of valve operation on the transient response of the study network, five different valve closure laws were considered. Three of these correspond to **linear closures**, in which the valve opening decreases at a constant rate throughout the maneuvers. The remaining two correspond to **multi-stage closures**, where the valve closing rate changes during the operation to reproduce more realistic operational procedures.

The linear closure laws were defined using total closure times of **15 s**, **40 s**, and **80 s**, representing rapid, intermediate, and slow valve operations, respectively. These scenarios were selected to evaluate the influence of the overall closure duration on the magnitude and propagation of transient pressure waves.

In addition to the linear closures, two variable-rate closure laws were implemented. The first, referred to as **Step 1**, consists of a rapid initial closure in which the valve reaches **80% of its total closure within the first 10 seconds**, followed by a considerably slower closure of the remaining **20% over the subsequent 45 seconds**. The second, referred to as **Step 2**, represents a three-stage maneuver in which **50% of the valve travel is completed during the first 30 seconds**, followed by **35% during the next 25 seconds**, and finally the remaining **15% during the last 20 seconds**.

These two multi-stage closure laws were introduced to represent valve operations in which the closure rate is intentionally modified during the maneuver. Such operating procedures are frequently adopted in practice to reduce the magnitude of transient pressures while maintaining operational control of the system. Consequently, the comparison between linear and multi-stage closures provides additional insight into the influence of valve operating strategies on the hydraulic response of the network.

Each closure law was independently combined with every selected valve and both initial operating conditions described in the previous section. This systematic combination generated the complete set of transient simulation scenarios analyzed in this research and allowed the individual influence of valve operation and initial hydraulic conditions to be evaluated.

Figure 4.5 illustrates the five valve closure laws adopted in this investigation, while **Table 4-2** summarizes their principal characteristics.

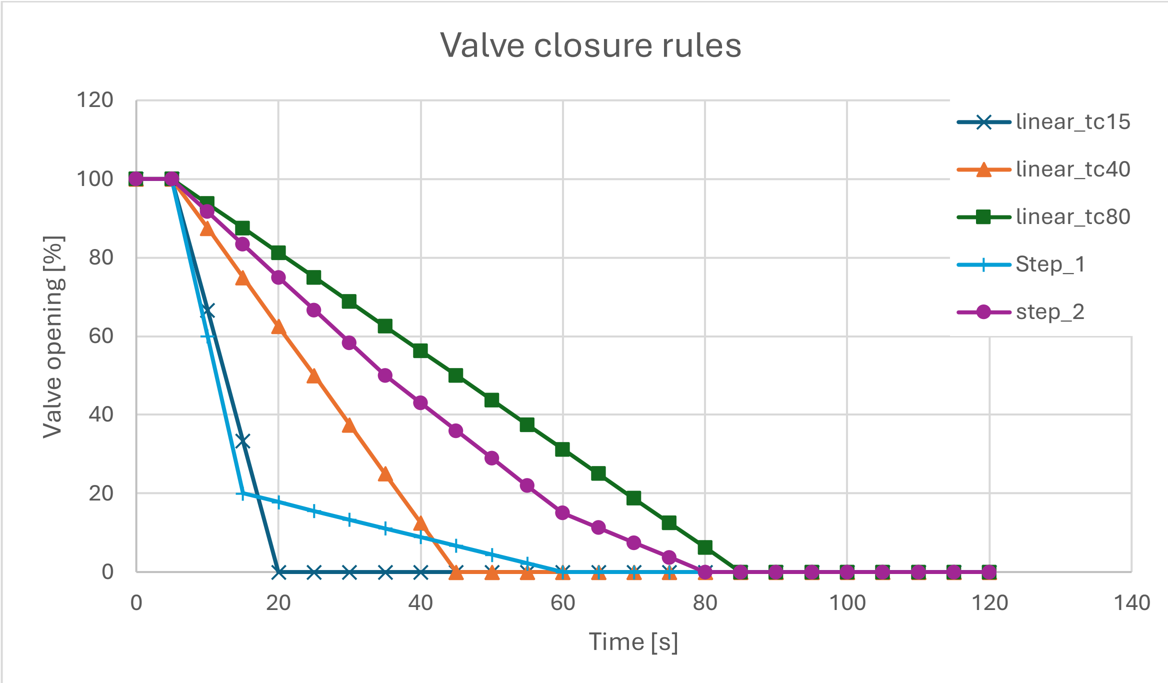


Figure 4.5 Valve closure rules

Table 4-2 Valve closure rules characteristics

Closure law	Stage 1		Stage 2		Stage 3		
	closure [%]	time [s]	closure [%]	time [s]	closure [%]	time [s]	Total time [s]
linear _tc15	100	15					15
linear_tc40	100	40					40
linear_tc80	100	80					80
step_1	80	10	100	45			55
Step_2	50	30	85	25	100	20	75

4.4.3 Numerical Simulation Parameters

The transient simulations were configured to ensure a consistent comparison between all valve closure scenarios while maintaining the numerical stability required by the Method of Characteristics. For this purpose, a common set of simulation parameters was adopted for every transient analysis performed in this research.

Each simulation was initialized from one of the two steady-state operating conditions described in Section 4.4.1 and subsequently subjected to one of the five valve closure laws presented in the previous section. The transient response was then computed over a predefined simulation period using a constant computational time step. This procedure ensured that all valve closure scenarios were evaluated under identical numerical conditions, allowing the influence of the valve operation itself to be isolated from numerical effects.

The wave propagation velocity assigned to each pipeline was defined according to its construction material. Since the wave speed depends on both the mechanical properties of the pipe wall and the compressibility of the fluid, representative values were assigned individually to each pipe material in order to reproduce the transient behavior of the real distribution system as accurately as possible. The adopted wave speed values are summarized in **Table 4-3**.

Table 4-3 Adopted wave speeds by material

Material	**Typical value [m/s]**	**Representative value [m/s]**	**Description**
DI	950-1200	1100	DUCTIL IRON
CI	1000-1300	1150	CAST IRON
CCP	1000-1400	1200	PRESTRESSED CONCRETE
ST	1100-1250	1250	STEEL
AC	900-1200	1000	ASBESTOS CEMENT
PVC	300-500	400	POLYVINYL CHLORIDE
HDPE	250-450	350	HIGH-DENSITY POLYETHYLENE

During each transient simulation, the temporal evolution of hydraulic head, pressure and flow rate was computed at every computational node of the network. These results constituted the basis for the subsequent hydraulic and structural analyses described later in this chapter.

The principal simulation parameters adopted throughout this research are summarized in **Table 4-4**.

Table 4-4 Simulation parameters

Parameter	Value/Quantity	Description
START TIME OF THE SIMULATION	2	11:00 AM (39600 S) and 3:00 AM (10800 s)
VALVE CLOSURE LAWS	5	linear 15s, linear 40s, linear 80s, 2 step variations
SELECTED VALVES	20	Representative network's valves with highest initial flow
TIME STEP	0.01	Time variation (in seconds) between each calculation made by the program
SIMULATION DURATION	120	Total time (in seconds) simulated
WAVE SPEED ASSIGNMENT	-	Values assigned for each pipe in function of its material
SOFTWARE	-	Python package TSNet (MOC)

4.4.4 Automated Simulation Workflow

The number of transient scenarios considered in this investigation required the development of an automated simulation workflow. Since each selected valve was analyzed under multiple operating conditions and valve closure laws, manually configuring and executing every transient simulation would have been inefficient and prone to human error. Therefore, the complete simulation process was automated using Python scripts developed specifically for this research.

The automation workflow systematically combined the two initial operating conditions, the twenty selected valves, and the five valve closure laws described in the previous sections. For each combination, the transient model was generated automatically, the corresponding valve closure event was applied, and the transient simulation was executed using TSNet. This procedure ensured that every scenario was analyzed using an identical computational procedure.

Upon completion of each simulation, the hydraulic results were automatically exported for subsequent processing. The generated outputs included the temporal evolution of hydraulic head, pressure, and flow variables required for the hydraulic and structural analyses presented later in this thesis. The automatic organization of simulation outputs also facilitated the comparison of different operating scenarios while ensuring the traceability and reproducibility of the complete methodology.

The automated workflow considerably reduced the computational effort associated with the transient analyses and eliminated inconsistencies that could arise from manually configuring a large number of simulation scenarios. In total, the proposed methodology generated **200**

independent transient simulations, corresponding to the combination of two initial operating conditions, twenty analyzed valves, and five valve closure laws.

Figure 4.6 summarizes the automated simulation workflow implemented in this research.

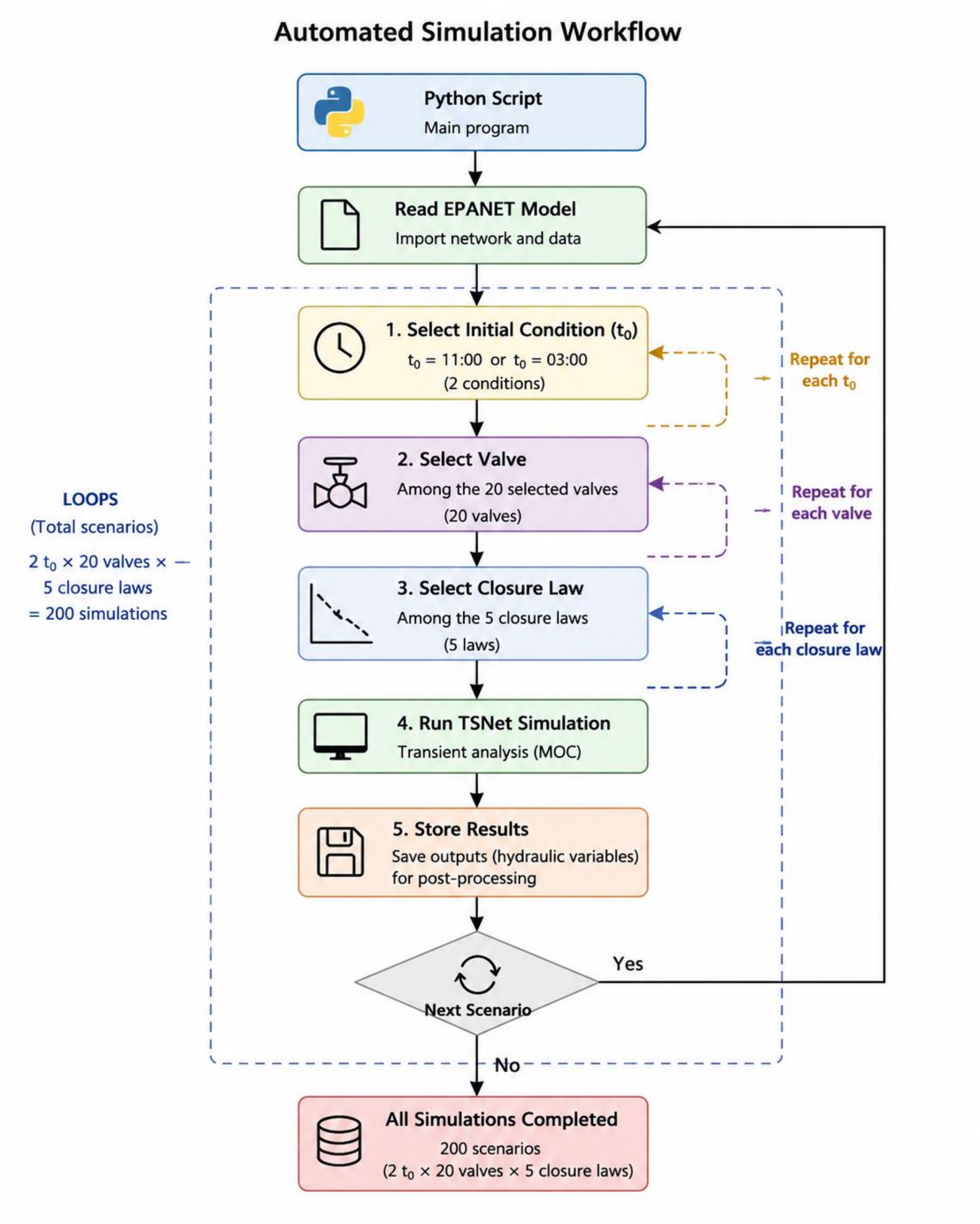


Figure 4.6 Automated simulation workflow

4.5 Post-Processing of Transient Results

The transient simulations performed using TSNet generated a large volume of hydraulic information, including the temporal evolution of hydraulic head, pressure and flow variables at every computational node of the network. Although these time series contain the complete hydraulic response of each simulation, their direct interpretation becomes impractical when analyzing a large number of transient scenarios. Consequently, a systematic post-processing procedure was developed to extract the hydraulic indicators required for the subsequent structural assessment and vulnerability analysis.

For each transient simulation, the temporal pressure history at every node was analyzed to identify the maximum and minimum pressures reached during the simulation period. These extreme values were selected because they represent the hydraulic conditions most relevant for evaluating the structural response of the pipeline system. The resulting pressure values were automatically exported to structured data files for subsequent analysis.

Since the structural assessment was performed at the pipe level rather than at individual nodes, the nodal pressure results were transformed into pipe-based hydraulic variables. For each pipeline, the representative transient pressure was defined as the **maximum pressure recorded at either of its two end nodes**. This conservative criterion ensures that the highest pressure capable of affecting the structural response of each pipeline segment is considered during the subsequent stress calculations.

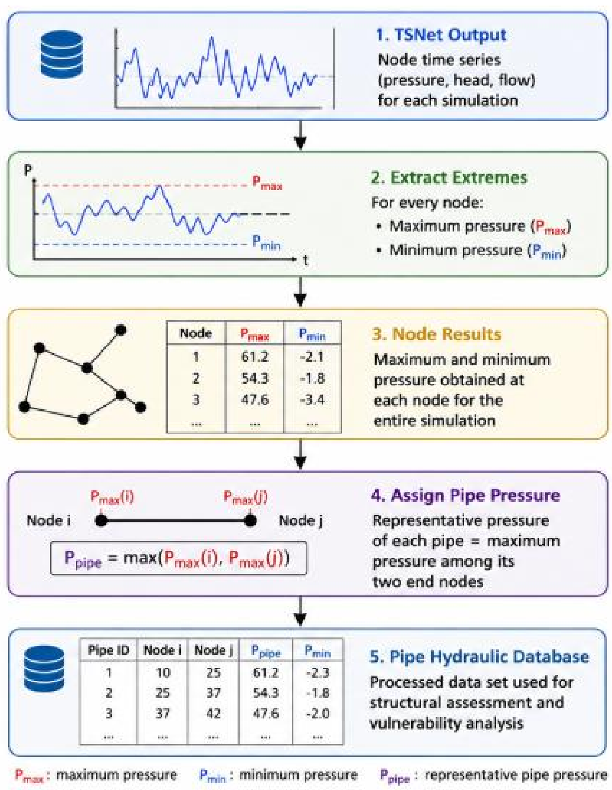


Figure 4.7 Post processing workflow

The post-processing procedure was fully automated using Python scripts developed specifically for this research. In addition to extracting the maximum and minimum pressures, the workflow organized the simulation outputs according to the analyzed valve, initial operating condition, and valve closure law, considerably simplifying the comparison of different transient scenarios.

The processed hydraulic datasets obtained in this stage constitute the input for the structural assessment of the pipeline system described in the following section.

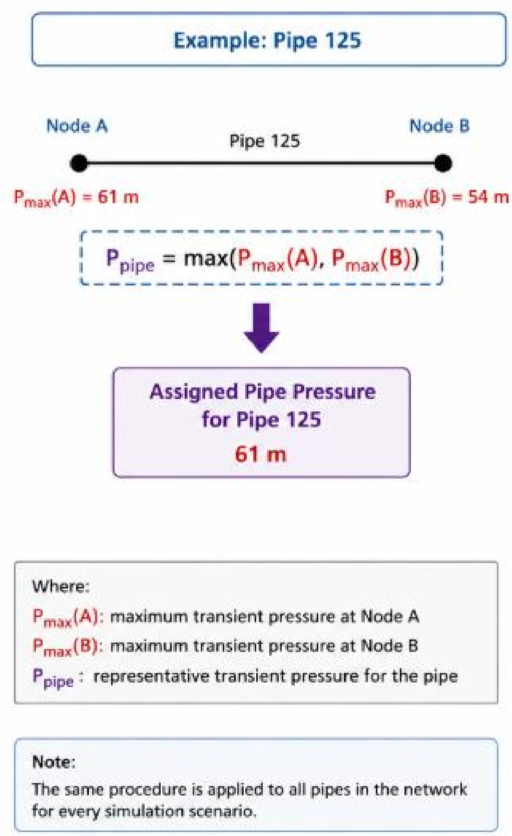


Figure 4.8 Example of pipe pressure assignment

4.6 Structural Assessment Methodology

The hydraulic variables obtained from the transient simulations provide valuable information regarding the pressure response of the water distribution network. However, pressure alone does not directly indicate the structural consequences of a transient event. For this reason, an additional structural assessment was performed to evaluate the mechanical demand imposed on the pipeline system.

The structural assessment was based on the circumferential stress (hoop stress) developed in the pipe wall as a consequence of the transient internal pressure. For each pipeline, the representative transient pressure obtained through the post-processing procedure described in the previous section was used to calculate the corresponding hoop stress assuming thin-walled cylinder behavior.

$$\sigma_h = P \cdot \frac{D}{2e} \tag{4.2}$$

Where:

- σ_h= circumferential (hoop) stress [Pa]
- P= representative transient internal pressure [Pa]
- D= internal pipe diameter [m]
- e= pipe wall thickness [m]

The geometric characteristics of each pipeline, including diameter and wall thickness, were obtained directly from the hydraulic model. Consequently, the circumferential stress was calculated individually for every pipe in the study network and for every simulated transient scenario.

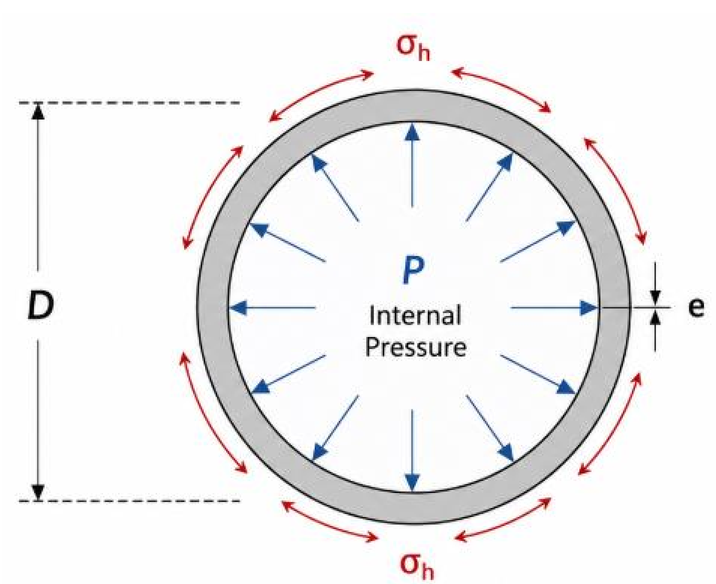


Figure 4.9 Hoop stress in pressurized pipe

Because the available information did not include the detailed mechanical properties of every individual pipeline, the structural capacity was evaluated according to the construction material of each pipe. The representative allowable and resistant stresses adopted in this study were compiled from commonly accepted values reported in technical literature and water pipeline design manuals. [2] Their purpose is to provide a consistent comparative basis for the proposed vulnerability assessment rather than to reproduce the certified mechanical properties of individual pipelines.

Table 4-5 Typical resistant stress

Material	Resistant stress [MPa]	Safety factor	Allowable stress [MPa]
ST	240	1.5	160
DI	300	2	150
CI	150	3	50
CCP	35	3	11.7
AC	15	3	5
PVC	50	2.5	20
HDPE	25	2.5	10

The comparison between the calculated hoop stress and the representative mechanical capacity of each material made it possible to estimate the relative structural demand imposed on every pipeline. Rather than providing an absolute prediction of structural failure, this methodology establishes a consistent basis for comparing the relative vulnerability of different sectors of the network under identical transient loading conditions.

The resulting structural indicators constitute the basis for the spatial vulnerability assessment presented in the following section.

4.7 GIS-Based Vulnerability Assessment

The final stage of the proposed methodology consisted of integrating the hydraulic and structural results within a Geographic Information System (GIS) to facilitate the interpretation of the transient analyses and identify the most vulnerable sectors of the study network. While numerical simulations provide detailed hydraulic information for every individual pipeline, the spatial representation of these results considerably improves their interpretation from an operational and asset management perspective.

The processed datasets obtained from the transient simulations and the structural assessment were exported in a format compatible with GIS software. Each pipeline of the network was associated with the corresponding hydraulic and structural indicators calculated during the previous stages of the methodology, allowing every pipe segment to be represented according to its transient response.

Four principal thematic maps were generated for each operating condition and each valve closure law. These maps represent:

- Maximum transient pressure.

- Minimum transient pressure.
- Ratio between the calculated hoop stress and the allowable stress.
- Ratio between the calculated hoop stress and the representative resistant stress.

For the pressure maps, the representative pressure assigned to each pipe corresponds to the maximum pressure recorded at either of its two end nodes, following the criterion described in Section **4.5**. Likewise, structural maps were generated using the hoop stresses calculated from these representative pressures, allowing the relative structural demand to be visualized throughout the network.

Since multiple valve closure locations were analyzed for every operating condition and closure law, the GIS layers were generated by assigning to each pipeline the **most critical value obtained among all simulated valve closures**. Consequently, each thematic map represents the worst transient condition experienced by every pipeline for the corresponding operating scenario. This approach provides a conservative representation of the spatial distribution of hydraulic and structural vulnerability within the analyzed network.

The resulting GIS products constitute the principal tool for interpreting the outcomes of the proposed methodology, enabling the rapid identification of critical sectors where transient pressures or structural demands are consistently higher than in the remainder of the distribution system.

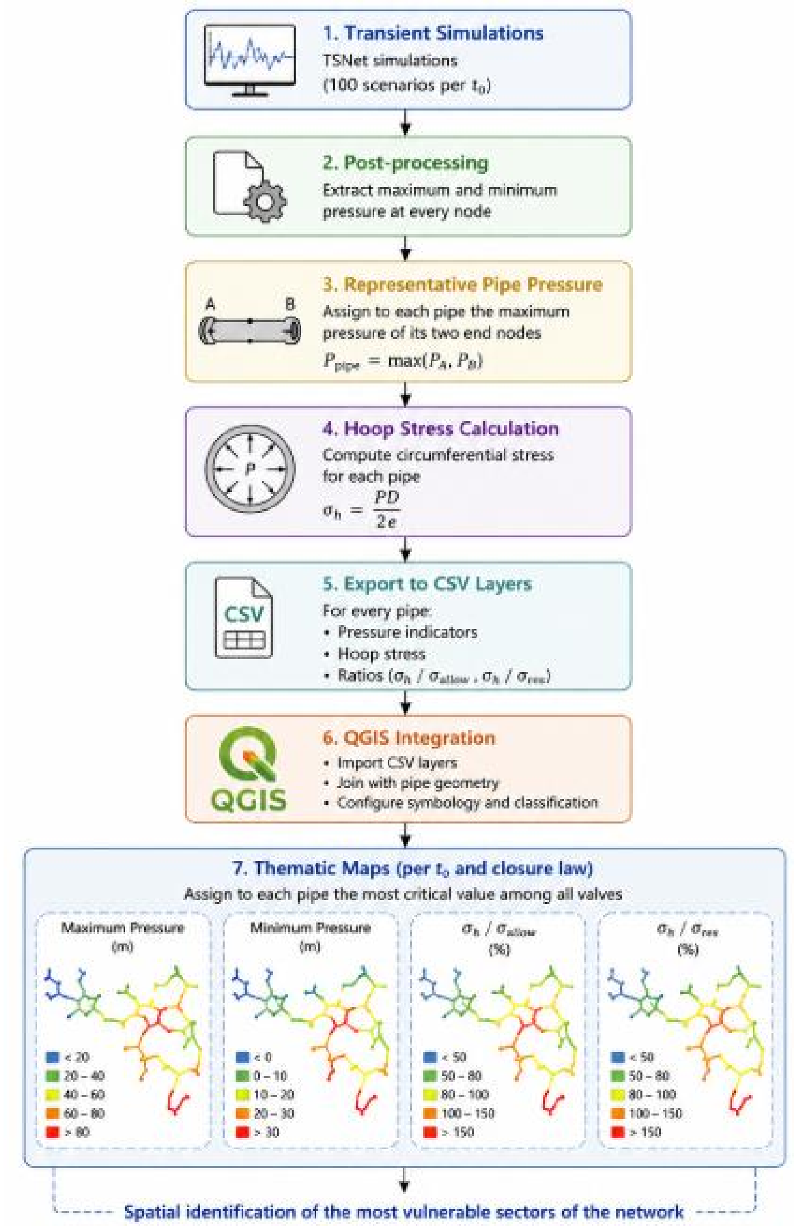


Figure 4.10 GIS-Based vulnerability assessment workflow

5 Results and Discussion

The methodology presented in Chapter **4** generated a comprehensive set of transient simulation results describing the hydraulic response of the study network under different operating conditions and valve closure laws. This chapter presents and discusses the principal findings obtained from these simulations, with particular emphasis on the influence of valve operation, initial hydraulic conditions and pipe material on the transient behavior of the network.

The discussion progresses from the analysis of representative transient responses to the structural assessment of the pipeline system and the identification of vulnerable sectors through GIS-based spatial analysis. This organization allows the hydraulic phenomena, structural implications and practical applications of the proposed methodology to be examined in a logical and progressive manner.

5.1 General Hydraulic Response Under Valve Closure Events

To illustrate the hydraulic behavior produced by a transient event, a representative valve closure scenario is analyzed in this section. The selected case corresponds to the valve presenting the highest steady-state flow velocity under the high-demand operating condition (11:00 AM) and a linear valve closure with a duration of 15 s. This scenario was selected because it produces one of the most pronounced transient responses observed during the simulations and clearly illustrates the principal hydraulic phenomena discussed in Chapter 2.

The transient response is analyzed through the pressure evolution immediately upstream and downstream of the operated valve. These locations provide a clear representation of the pressure waves generated by the valve closure and their subsequent propagation throughout the network.

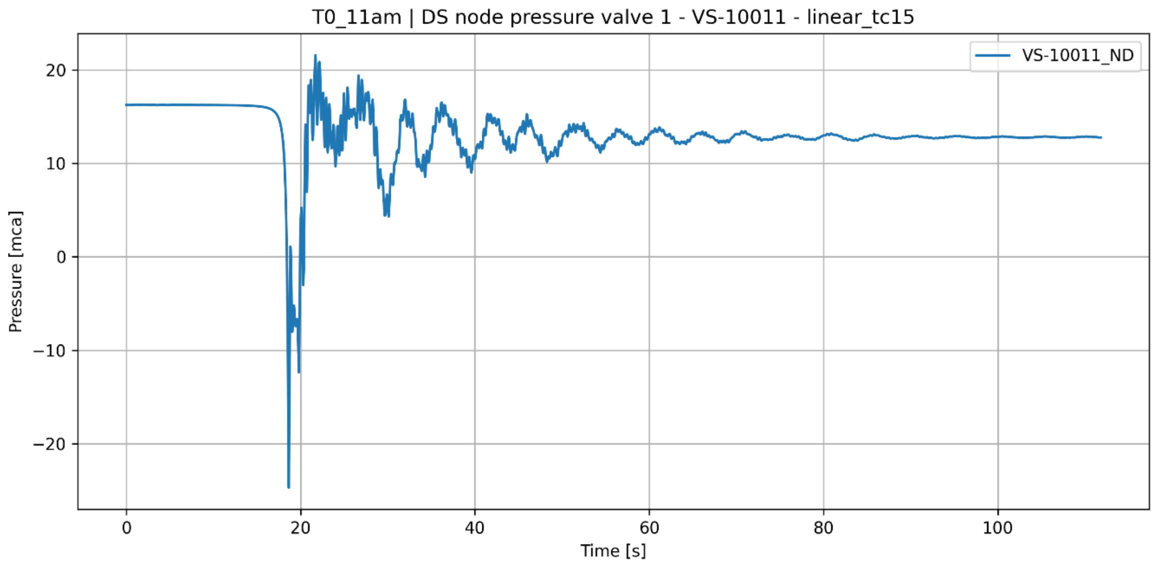


Figure 5.1 DS node pressure of valve VS-10011 at 11:00AM with Tc 15 s

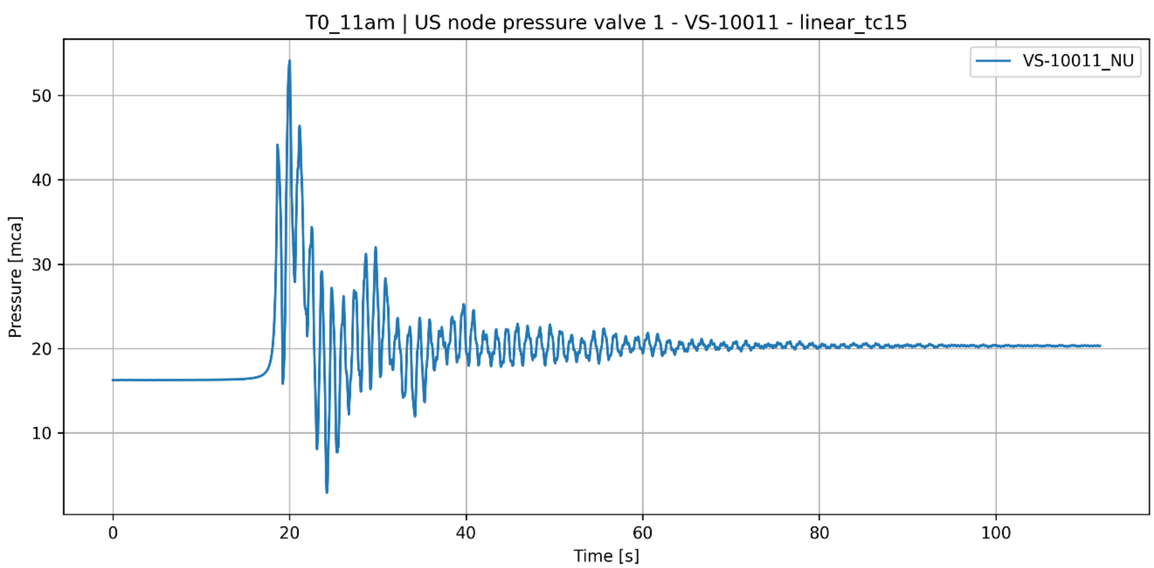


Figure 5.2 US node pressure of valve VS-10011 at 11:00AM with Tc 15 s

Immediately after the valve closure begins, the hydraulic response differs significantly on the two sides of the valve. As shown in **Figure 5.2**, the upstream node experiences a rapid increase in pressure caused by the deceleration of the flowing water. This compression wave reaches its maximum value shortly after the initiation of the valve maneuver and is followed by a sequence of oscillations whose amplitude gradually decreases due to hydraulic damping within the network.

In contrast, the downstream node exhibits the opposite hydraulic behavior. As illustrated in **Figure 5.1**, the interruption of the incoming flow produces a sudden pressure reduction immediately downstream of the valve, generating a transient depression before the pressure progressively recovers. The subsequent oscillations also decay with time as pressure waves propagate, reflect at hydraulic boundaries, and dissipate energy throughout the network.

The comparison between the upstream and downstream pressure histories clearly demonstrates the characteristic behavior of valve-induced hydraulic transients in pressurized pipe systems. While the upstream side is dominated by compression waves associated with flow deceleration, the downstream side experiences an initial pressure deficit caused by the temporary reduction of flow supply. These opposite responses are consistent with the theoretical principles presented in Chapter **2** and confirm that the numerical simulations reproduce the expected physical behavior of transient wave propagation.

As the transient progresses, both pressure signals exhibit progressively smaller oscillation amplitudes until a new hydraulic equilibrium is reached. The gradual attenuation of the pressure fluctuations indicates the dissipation of transient energy within the network and the establishment of a new steady-state condition following completion of the valve closure.

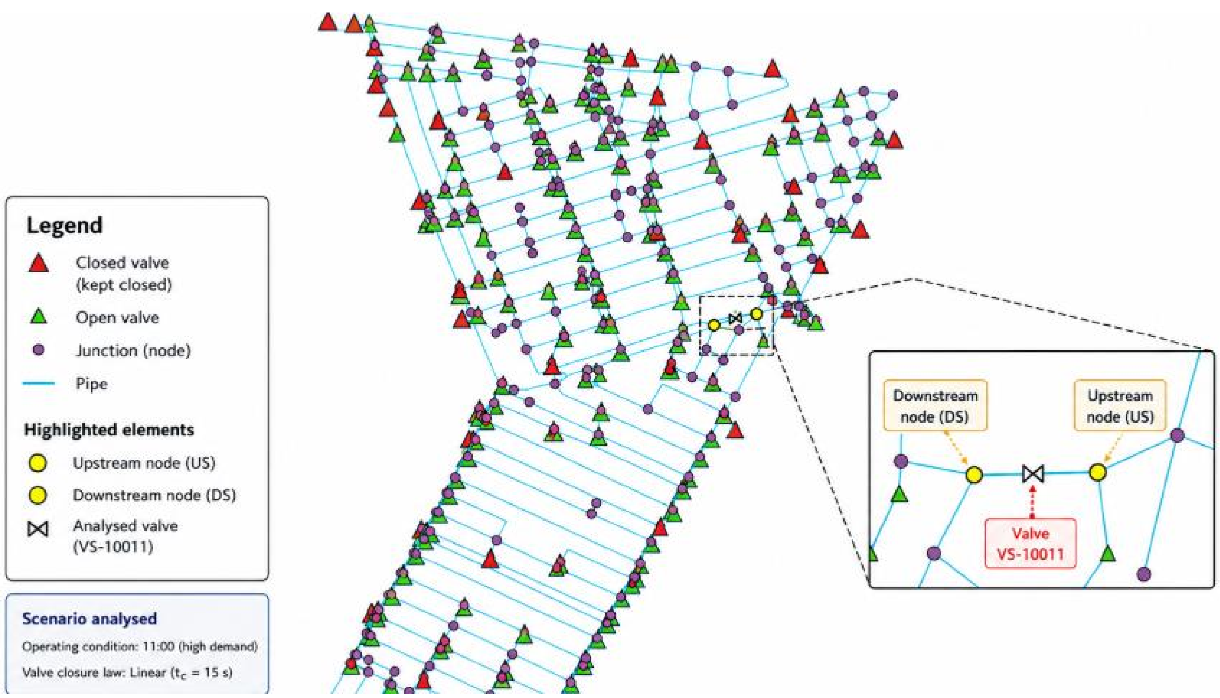
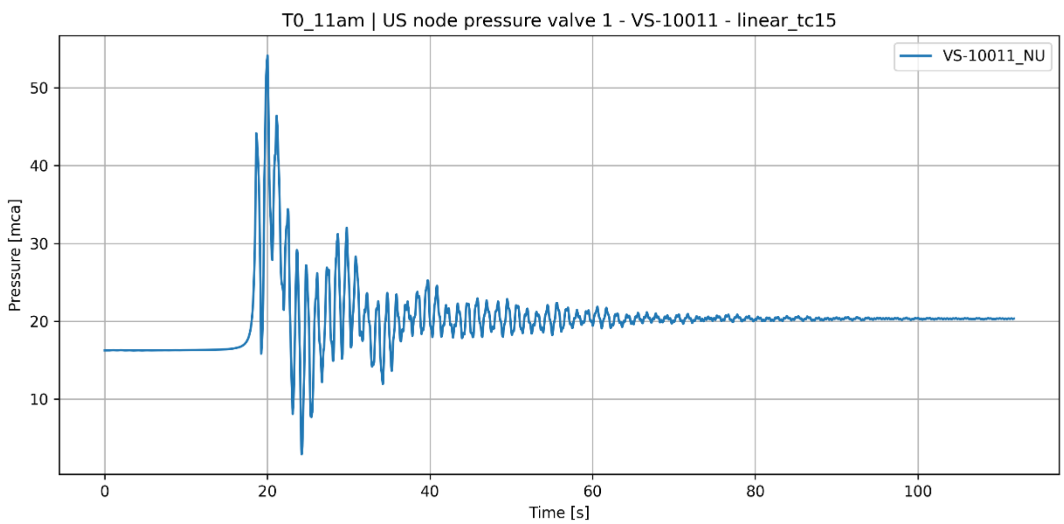


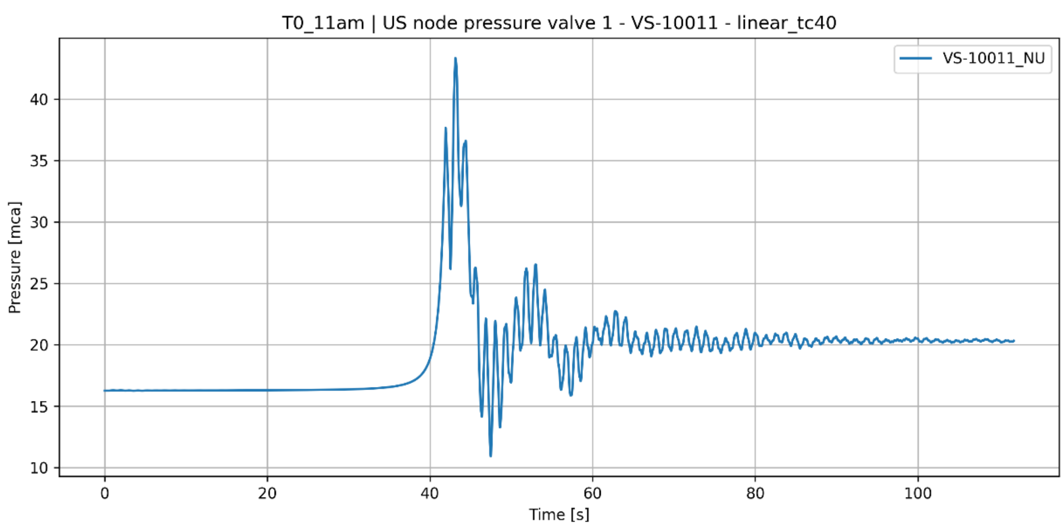
Figure 5.3 Analyzed valve location

5.2 Influence of Valve Closure Laws

The hydraulic response generated by a transient event is strongly influenced by the way in which a valve is operated. While the total closure time is widely recognized as one of the principal parameters governing pressure surges, the numerical simulations performed in this study indicate that the temporal distribution of the valve movement also plays an important role in determining the magnitude and evolution of transient pressures.

To investigate this effect, the five valve closure laws presented in Chapter 4 were applied to the valve exhibiting the highest steady-state flow velocity under the high-demand operating condition (11:00). The pressure histories immediately upstream and downstream of the valve were subsequently analyzed in order to evaluate the influence of different operating strategies on the transient response.





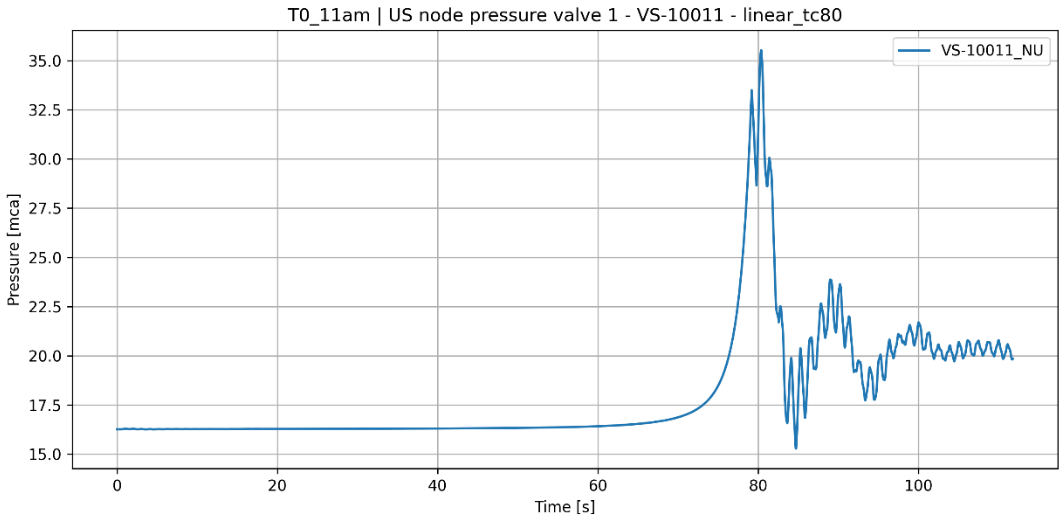


Figure 5.4 Upstream pressure time series for linear valve closures

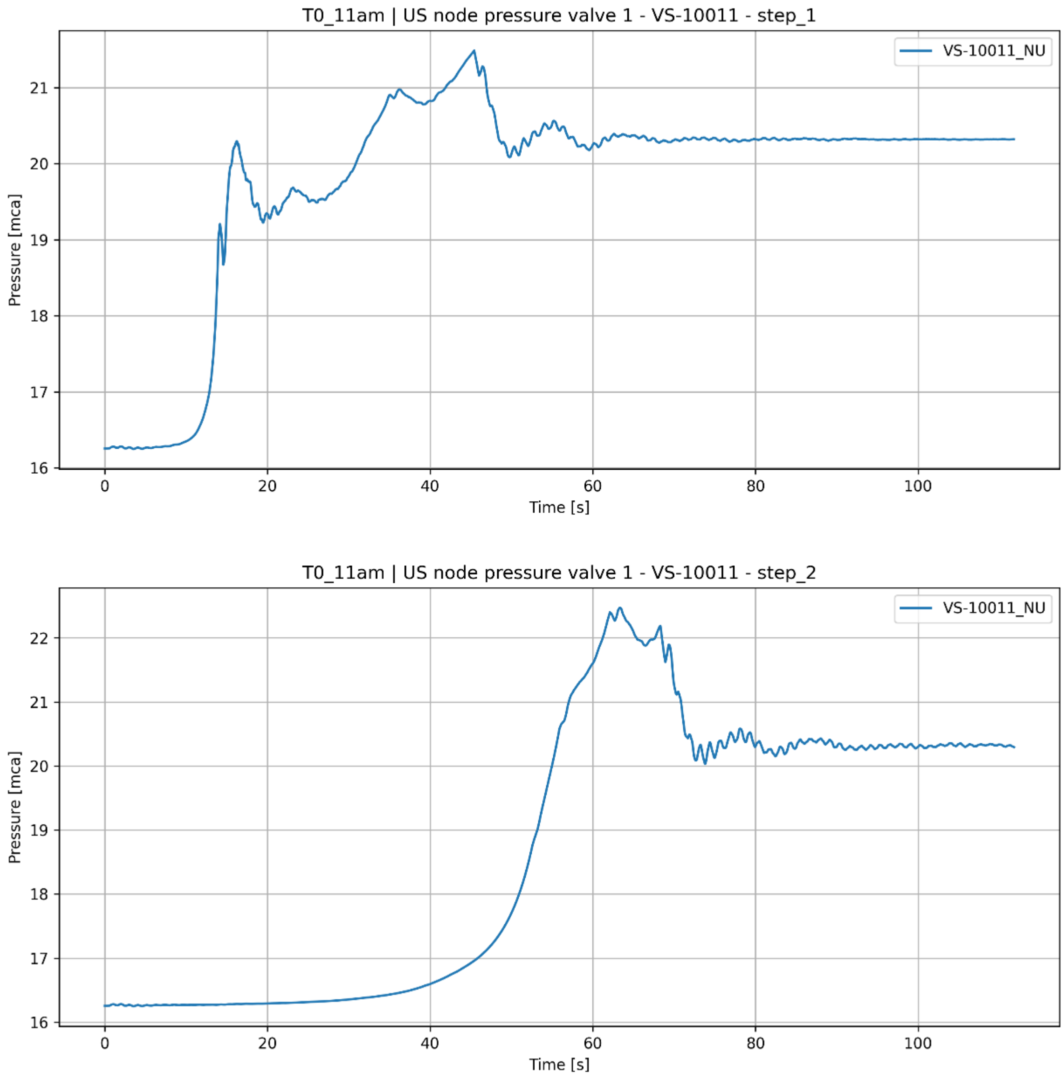


Figure 5.5 Upstream pressure time series for step valve closures

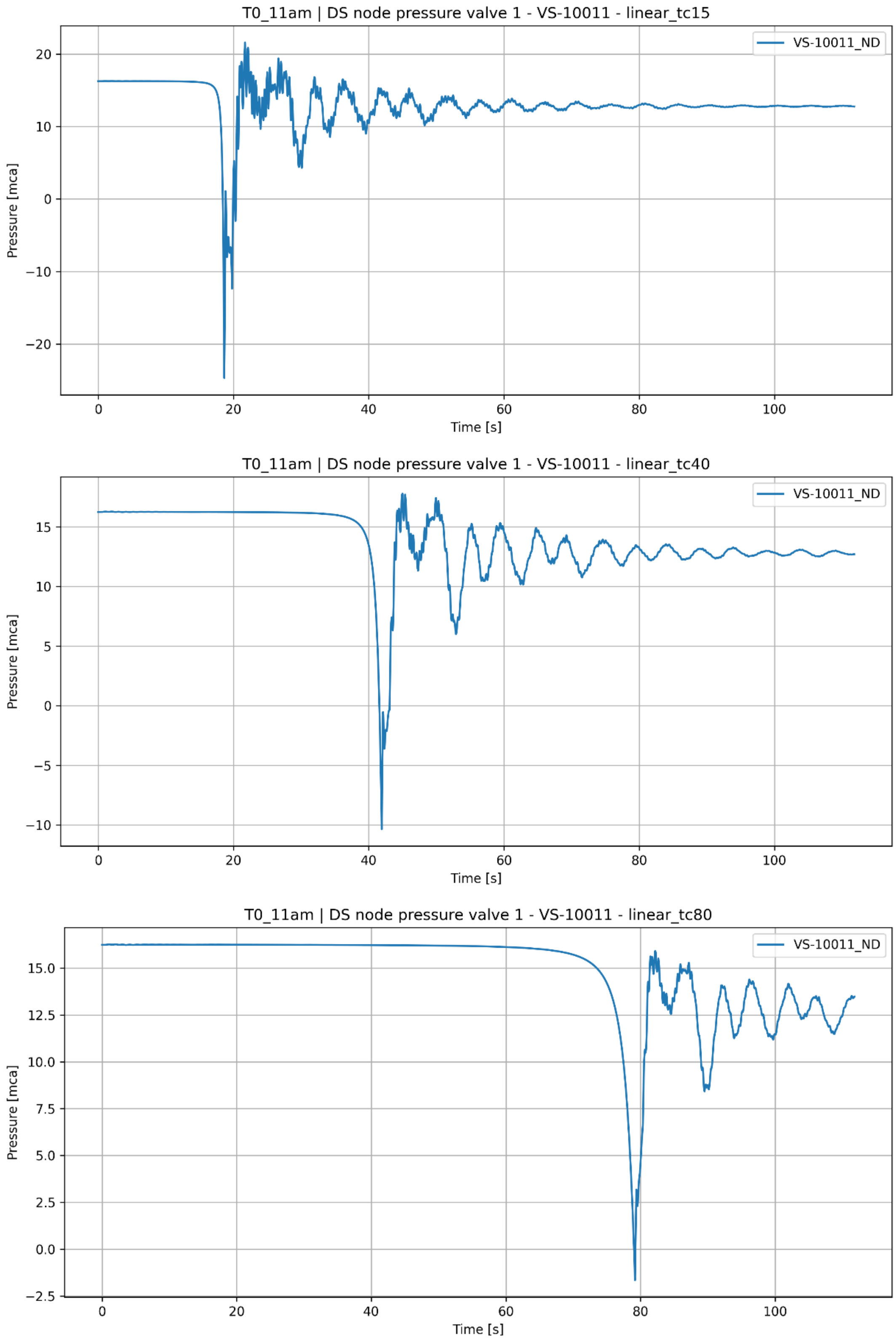


Figure 5.6 Downstream pressure time series for linear valve closures

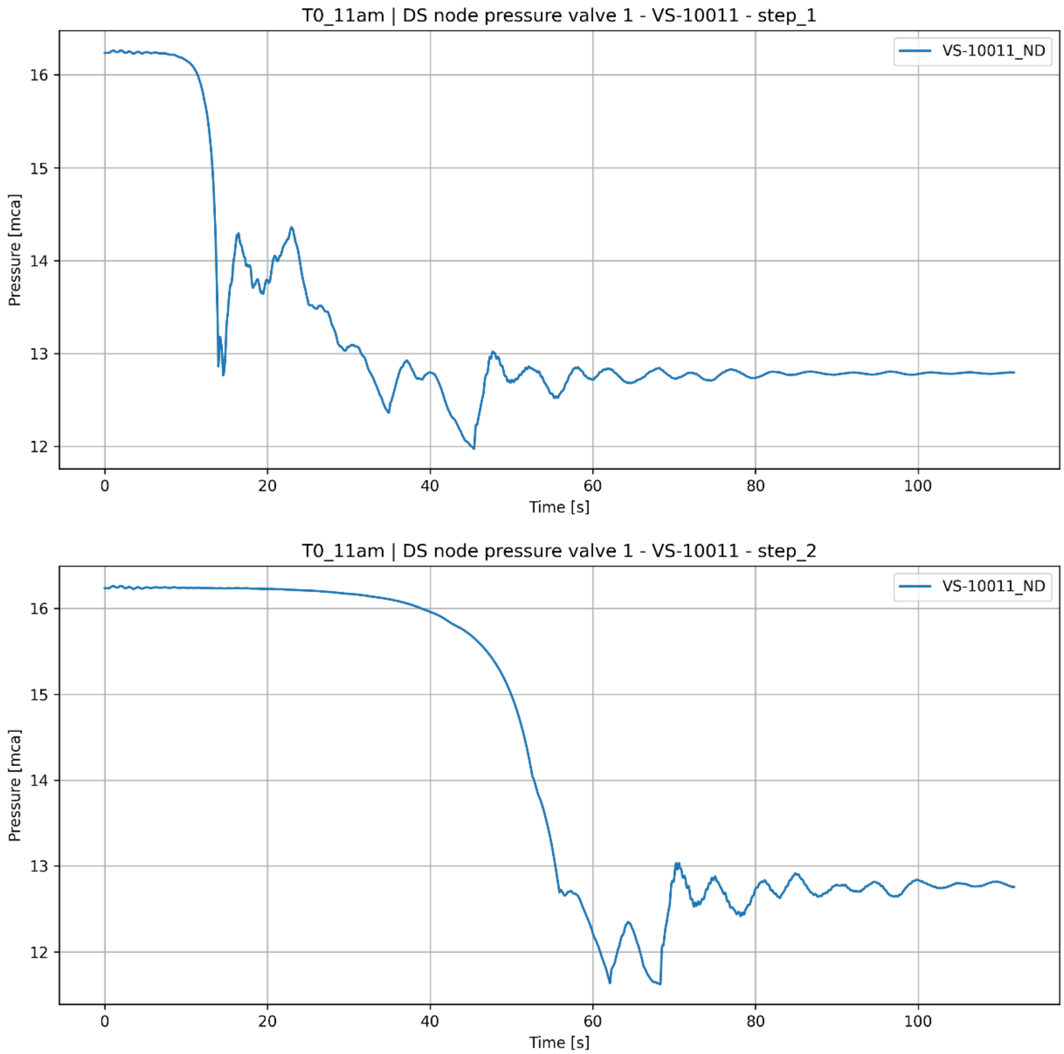


Figure 5.7 Downstream pressure time series for step valve closures

The three linear closure laws exhibit the expected behavior predicted by classical transient flow theory. The shortest maneuver (15 s) produces the largest pressure fluctuations, generating the highest compression peak upstream of the valve together with the most severe downstream pressure reduction. Increasing the closure duration to 40 s and subsequently to 80 s progressively reduces the magnitude of both the positive and negative pressure waves. Consequently, slower linear closures produce a less severe transient response throughout the system.

Another important difference among the linear maneuvers is the timing of the transient event. For the 15 s closure, the principal pressure peak develops shortly after the valve begins to close. In contrast, for the 80 s closure the pressure remains close to its initial steady-state value during most of the maneuver, while the largest pressure variation occurs only near the final stages of valve closure. This behavior indicates that significant transient waves are generated primarily when the hydraulic resistance introduced by the valve becomes sufficiently large to produce a rapid reduction in flow velocity.

The two staged valve closure laws produce a substantially different hydraulic response. Although both maneuvers ultimately achieve complete valve closure, the progressive distribution of the valve movement considerably reduces the transient intensity. Rather than producing a single abrupt change in flow conditions, the staged maneuvers distribute the reduction in flow velocity over several phases of the operation, resulting in a smoother pressure evolution both upstream and downstream of the valve.

This behavior is clearly reflected in the pressure extremes summarized in **Table 5.1**. While the linear closure laws generate maximum upstream pressures ranging from 35.5 m to 54.1 m and downstream pressures as low as −24.7 m, the staged closure laws limit the maximum upstream pressure to approximately 22 m and completely eliminate the negative downstream pressures observed during the linear maneuvers. These results indicate that the staged operating strategies significantly mitigate both pressure surges and pressure deficits.

Table 5-1 Pressure extremes obtained for the analyzed valve under different closure laws.

Closure Law	Max upstream pressure [m]	Min Downstream pressure [m]
linear_tc15	54.1	-24.7
linear_tc40	43.3	-10.4
linear_tc80	35.5	-1.7
step_1	21.5	12.0
step_2	22.5	11.6

Overall, these results demonstrate that the transient response is governed not only by the total valve closure time but also by the temporal distribution of the closure process. While increasing the duration of a linear maneuver progressively reduces transient pressures, staged closure strategies provide an even greater reduction in pressure extremes by modifying the rate at which the flow decelerates throughout the operation. From an operational perspective, these findings suggest that appropriately designed valve operating strategies can significantly mitigate transient loads without relying exclusively on longer closure times.

5.3 Influence of Initial Hydraulic Conditions

The severity of a hydraulic transient depends not only on the valve operating strategy but also on the hydraulic state of the network immediately before the transient event occurs. Since water demand varies throughout the day, the initial flow velocities and pressure distribution within the network also change, modifying the amount of kinetic energy available to generate pressure waves during a valve closure.

To evaluate this effect, the transient response produced by the 15 s linear closure of valve VS-10011 was analyzed under the two representative operating conditions considered in this study: the high-demand period (11:00) and the low-demand period (03:00).

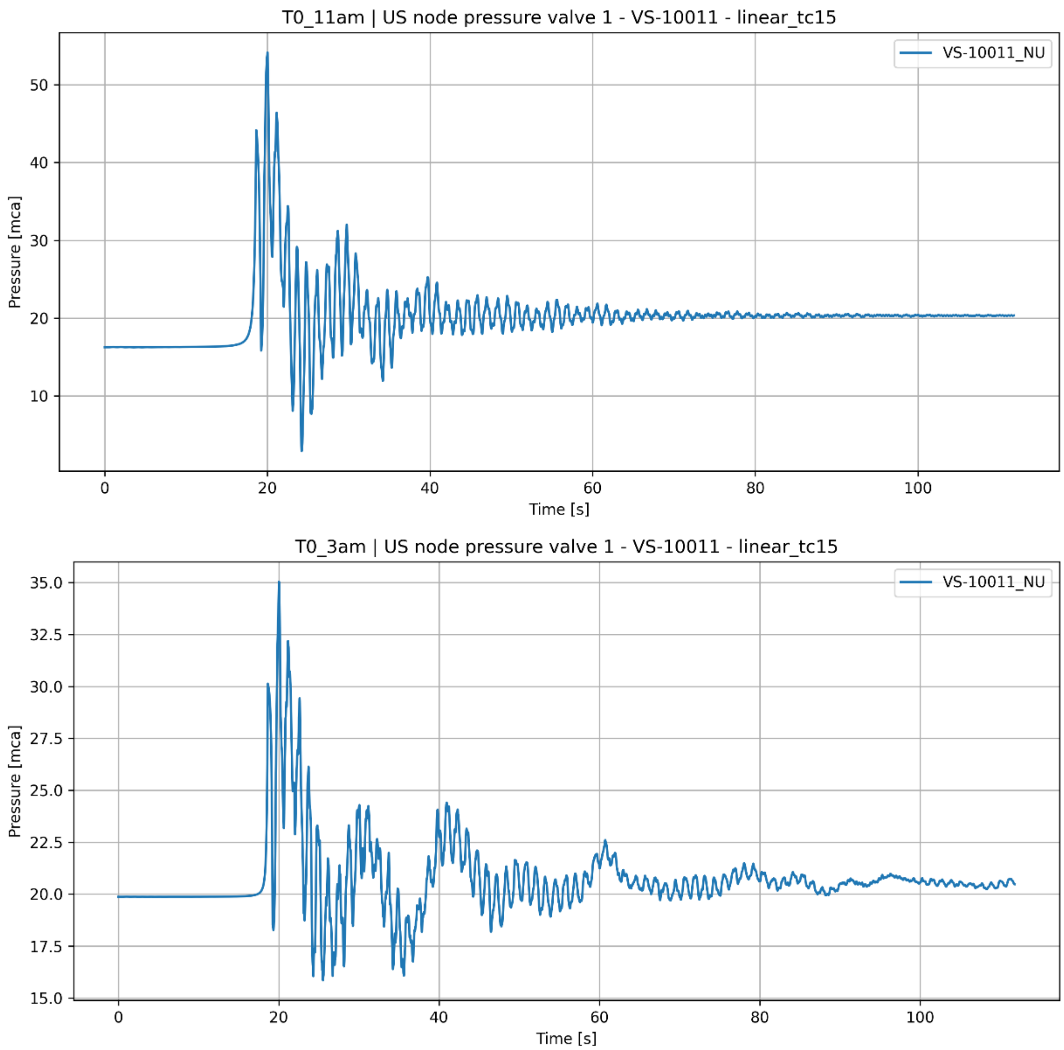
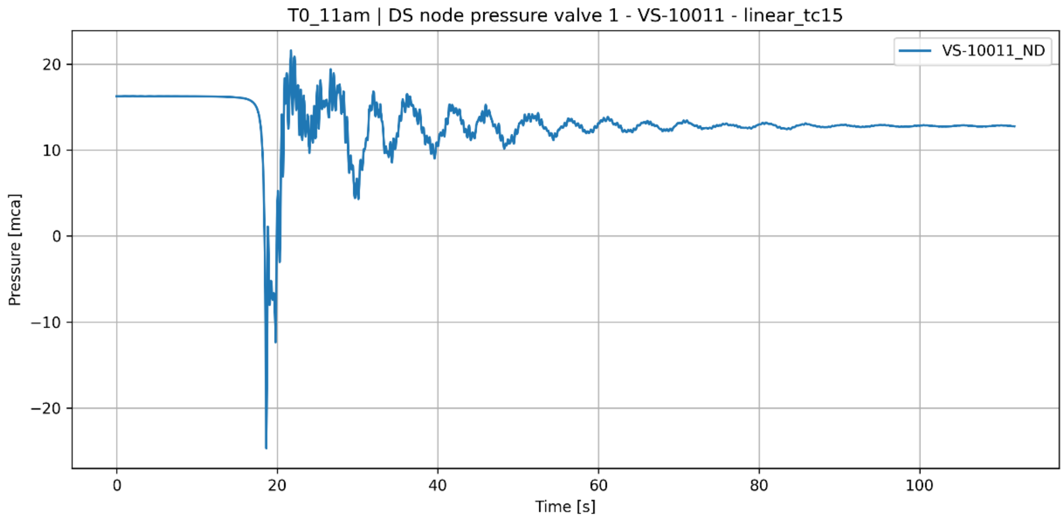


Figure 5.8 Upstream pressure response for the 15 s linear closure under the two operating conditions.



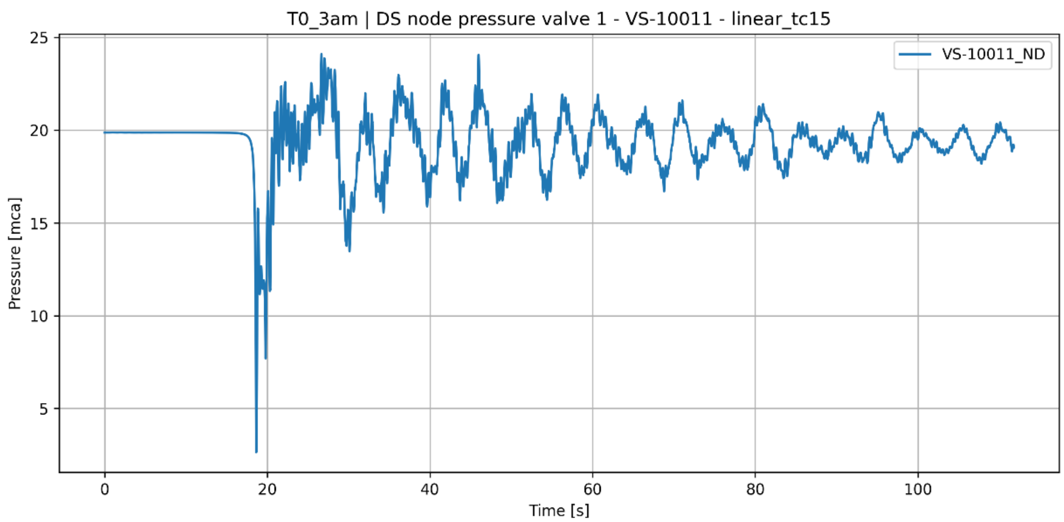


Figure 5.9 Downstream pressure response for the 15 s linear closure under the two operating conditions.

The pressure time series reveals a clear influence of the initial hydraulic conditions on the transient response. During the high-demand period, the valve operates under higher initial flow velocities, producing a significantly larger pressure surge upstream and a severe pressure reduction downstream immediately after the valve closure begins. In contrast, the same valve maneuver performed during the low-demand period generates considerably lower pressure fluctuations and a much smoother transient response.

The pressure extremes summarized in **Table 5-2** clearly quantify these differences. Under the high-demand condition, the maximum upstream pressure reaches 54.1 m, while the downstream pressure decreases to −24.7 m, indicating the occurrence of severe pressure deficits. Conversely, under the low-demand condition, the maximum upstream pressure is reduced to 35.0 m, and the minimum downstream pressure remains positive at 2.6 m, eliminating the risk of sub-atmospheric pressures for this particular maneuver.

Table 5-2 Comparison of pressure extremes for the 15 s linear valve closure under different operating conditions.

Operating condition	Maximum upstream pressure (m)	Minimum downstream pressure (m)
High demand (11:00)	54.1	-24.7
Low demand (03:00)	35	2.6

These observations are consistent with the theoretical principles presented in Chapter 2. According to the Joukowsky relationship, transient pressure variations are directly related to the change in flow velocity during the valve maneuver. Higher initial velocities during periods of elevated demand therefore produce larger pressure surges, whereas the reduced velocities observed during low-demand conditions lead to substantially lower transient loads.

From a practical perspective, these results highlight that the hydraulic vulnerability of a water distribution network cannot be evaluated considering only the valve operation itself. The same maneuver may produce markedly different pressure responses depending on the operating conditions of the network at the time of the event. Consequently, transient analyses intended to support operational decision-making should account for representative demand scenarios rather than relying on a single steady state condition.

5.4 Network-Wide Distribution of Transient Pressures

The analyses presented in the previous sections focused on the transient response generated at a representative valve location in order to illustrate the physical mechanisms associated with valve closure. Once these local hydraulic behaviors have been established, the analysis is extended to the entire water distribution network in order to identify the spatial distribution of transient pressure extremes.

To obtain a network-wide representation of the hydraulic response, the maximum and minimum transient pressures recorded at every node during each simulation were assigned to the corresponding pipelines using the methodology described in Chapter 4. For each pipe, the governing pressure was taken as the most critical value recorded at its two end nodes. Subsequently, for every closure law, the envelope of all valve simulations was calculated so that each pipeline was assigned the most severe pressure generated by any of the analyzed valve operations under the considered operating condition.

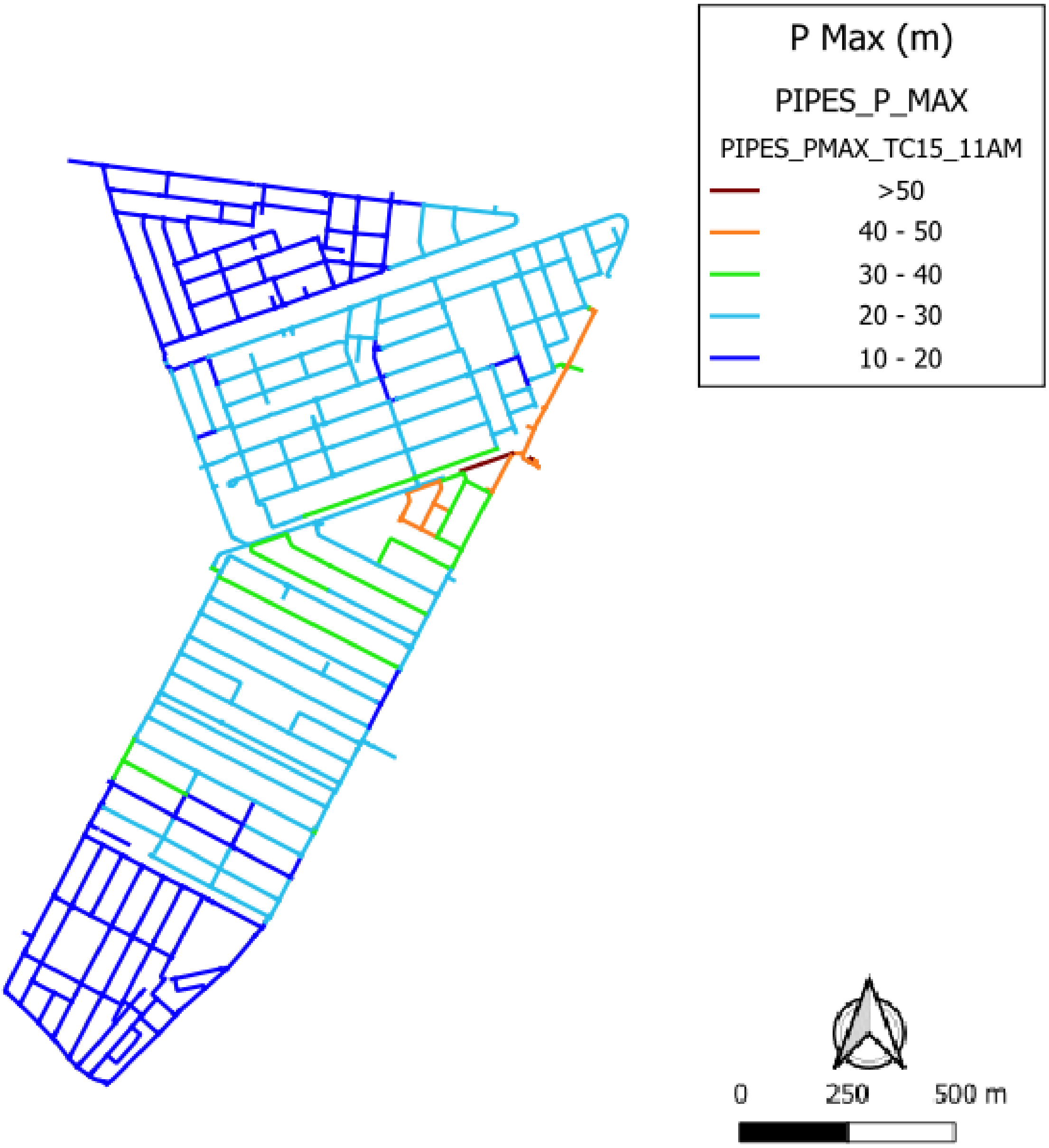


Figure 5.10 Envelope distribution of maximum transient pressures for the 11:00 operating condition (Linear 15 s closure).

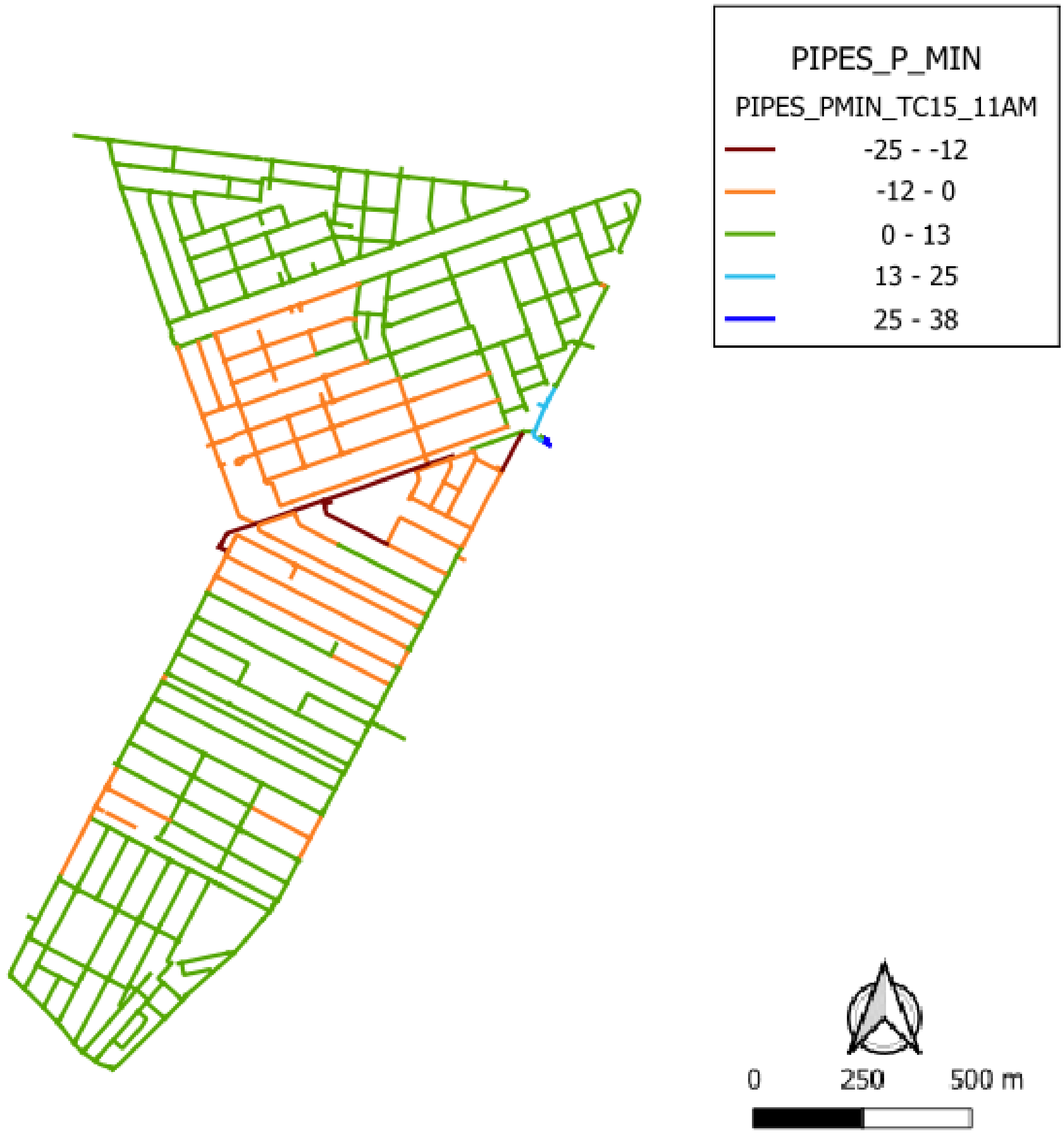


Figure 5.11 Envelope distribution of minimum transient pressures for the 11:00 operating condition (Linear 15 s closure).

The resulting pressure maps reveal that transient loads are not uniformly distributed throughout the network. Instead, pressure extremes are concentrated within relatively limited portions of the system, while a large proportion of the pipelines experience only moderate pressure variations. This behavior reflects the combined influence of network topology, wave propagation, hydraulic boundary conditions and the interaction between incident and reflected pressure waves within the branched distribution system.

The distribution of maximum pressures indicates that the highest compression waves tend to develop along the principal hydraulic paths connected to the operated valves, where the rapid reduction in flow velocity generates the greatest increase in pressure. In contrast, the minimum pressure map shows that the most severe pressure deficits are generally located downstream of the valve operations and along secondary branches, where wave reflections and local hydraulic conditions may amplify rarefaction waves.

An important characteristic of these envelope maps is that they represent the worst hydraulic condition that each pipeline may experience regardless of which valve initiates the transient event. Consequently, they provide a comprehensive assessment of the hydraulic demand imposed on every element of the network rather than describing the response associated with a single valve operation.

From an engineering perspective, these results demonstrate that evaluating only the vicinity of the operated valve is insufficient to characterize the hydraulic vulnerability of a water distribution network. Although the transient originates from a localized operation, the generated pressure waves propagate throughout the system and may produce critical hydraulic conditions at locations considerably removed from the initiating event. The envelope approach therefore constitutes an effective tool for identifying the portions of the network that require further structural assessment.

5.5 Structural Assessment of the Pipeline System

While transient pressure envelopes provide a direct measure of the hydraulic loading acting on the network, the structural integrity of a pipeline depends on the stresses induced within its wall rather than on pressure alone. For this reason, the pressure envelopes obtained in the previous section were transformed into circumferential (hoop) stresses using the methodology described in Chapter 4. The resulting stresses were subsequently compared with both the allowable stress and the resistant stress associated with each pipe material, providing a direct assessment of the structural demand imposed by transient events.

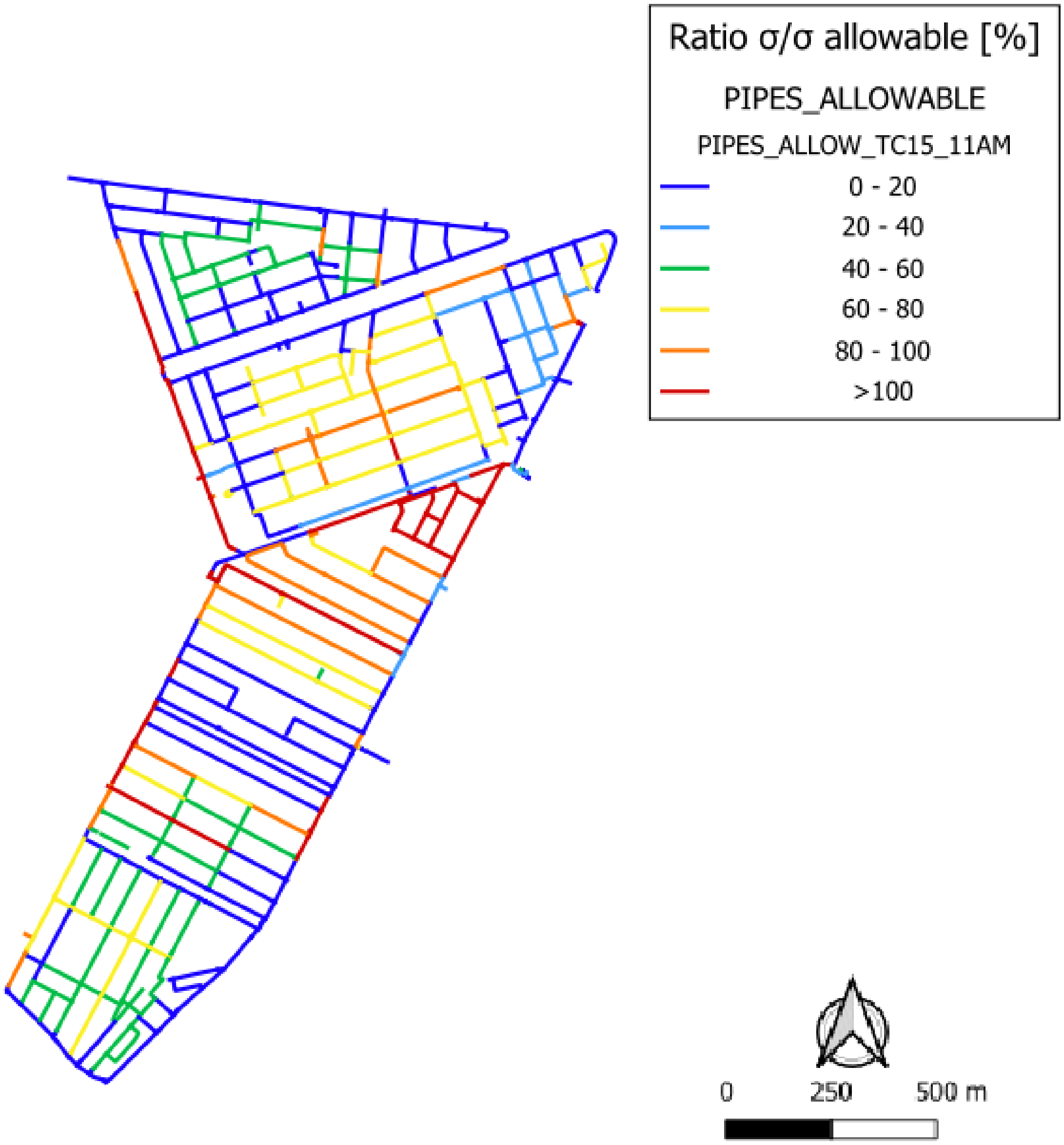


Figure 5.12 Distribution of hoop/allowable ratio with valve closure of 15 s

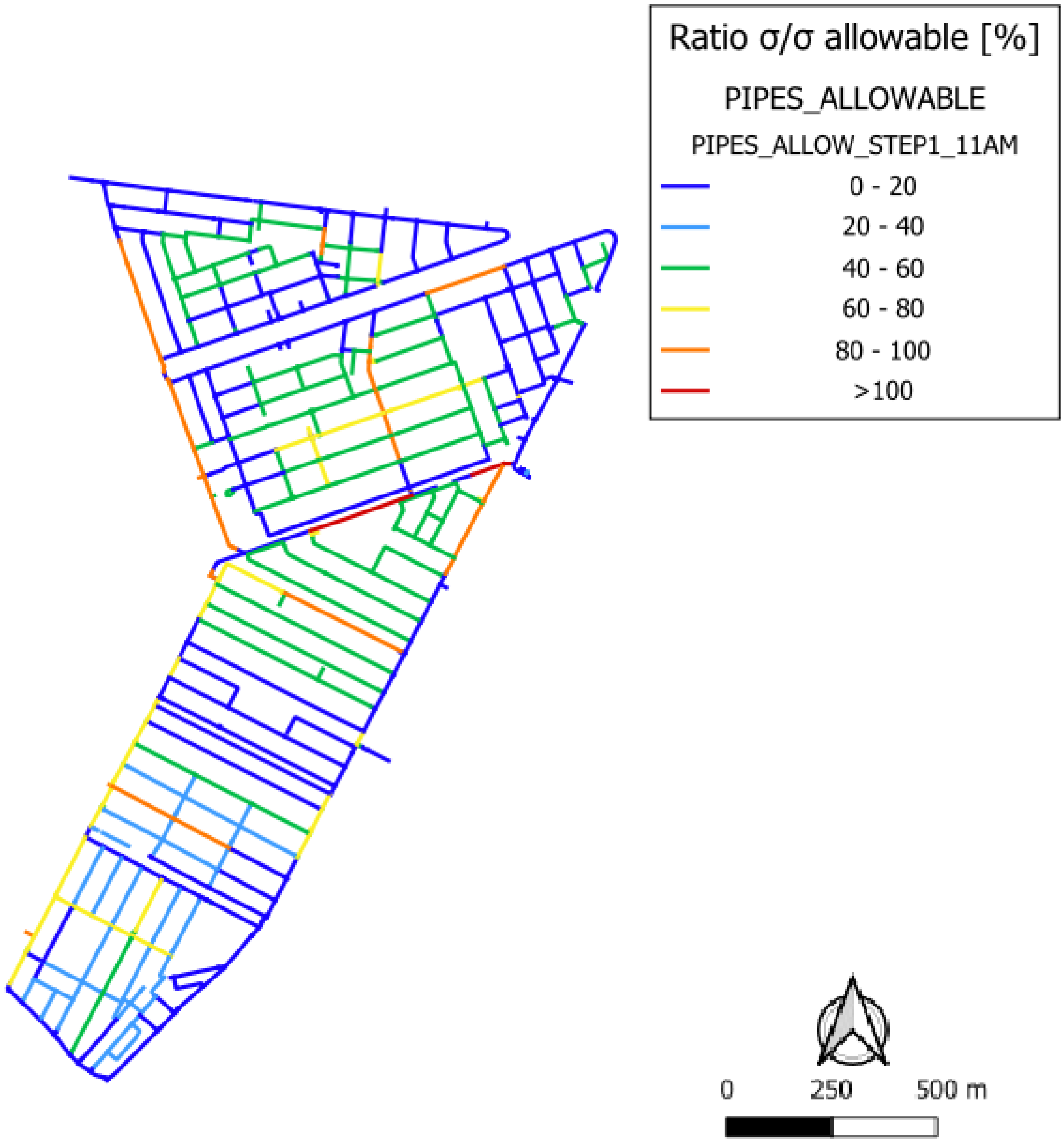


Figure 5.13 Distribution of hoop/allowable ratio with valve closure Step 1

The spatial distribution of hoop stresses follows the same general pattern observed for the transient pressure envelopes, with the highest stress occurring along the principal hydraulic paths connected to the operated valves. However, the structural assessment reveals that the mechanical response of the network cannot be interpreted solely from pressure magnitudes. Differences in pipe diameter, wall thickness and material properties significantly influence the resulting stress levels and, consequently, the structural vulnerability of individual pipelines.

Table 5-3 summarizes the maximum structural indicators obtained for the five valve closure strategies under the high-demand operating condition (11:00). Although the maximum hoop stress varies only moderately, from **16.49 MPa** to **17.38 MPa**, the corresponding utilization of the allowable and resistant stresses changes considerably depending on the adopted closure law.

Table 5-3 Maximum structural demand indicators for the analyzed closure laws (11:00 operating condition).

Closure law	Maximum hoop stress (MPa)	Maximum σ/σ_allowable (%)	Maximum σ/σ_resistant (%)
Linear 15 s	17.38	331.7	110.6
Linear 40 s	16.83	265.6	88.5
Linear 80 s	16.61	217.8	72.6
Step 1	16.5	131.7	43.9
Step 2	16.49	137.7	45.9

The results clearly indicate that the valve closure strategy has a much greater influence on the structural safety margins than on the absolute hoop stress values. The conventional linear closure of 15 s produces the highest structural demand, exceeding both the allowable stress and the estimated resistant stress in the most critical pipeline. Increasing the closure duration progressively reduces stress utilization, while the staged closure strategies provide the lowest structural demand, reducing the maximum utilization of the resistant stress to less than half of that produced by the fastest linear closure.

An important observation is that the pipelines subjected to the highest hoop stresses are not necessarily those identified as structurally most vulnerable. The largest absolute hoop stresses are developed in **steel pipelines**, whose high mechanical strength allows these stresses to remain well below their allowable limits. Conversely, the highest stress utilization ratios are consistently observed in **pipeline TU-27423**, constructed from **asbestos cement (AC)**. Although this pipe does not experience the largest absolute stress, its relatively low allowable stress results in the highest structural demand within the network.

This distinction demonstrates that evaluating transient events exclusively through pressure or hoop stress may lead to misleading conclusions regarding pipeline vulnerability. Structural performance depends on the combined effect of hydraulic loading, pipe geometry and material resistance. Consequently, stress utilization ratios provide a more representative indicator of structural safety than pressure or hoop stress alone.

Overall, the proposed methodology enables hydraulic transient simulations to be directly linked with the structural performance of water distribution systems. By integrating transient pressure analysis with material-dependent mechanical criteria, it becomes possible to identify not only where the highest pressures occur, but also which pipelines are genuinely the most vulnerable from a structural perspective.

6 Conclusion and Future Work

This chapter summarizes the principal findings of the research and discusses their implications for the analysis and management of hydraulic transients in water distribution networks. The main contributions of the proposed methodology are highlighted, followed by a discussion of its practical applications, the principal limitations of the study, and recommendations for future research.

6.1 Main Conclusions

The present research developed and validated a comprehensive methodology for assessing the effects of hydraulic transients in water distribution networks by integrating steady-state hydraulic modelling, transient flow simulations, structural assessment and GIS-based spatial analysis. The proposed workflow combines EPANET for steady-state simulations, TSNet for transient modelling, Python-based post-processing for the calculation of structural indicators, and GIS tools for the visualization of hydraulic and structural vulnerability. This integrated approach provides a practical framework for evaluating transient events in real water distribution systems and can be readily adapted to other networks with similar characteristics.

The transient simulations demonstrated that valve closure operations produce pressure waves capable of propagating throughout the entire distribution network, generating hydraulic effects far beyond the vicinity of the operated valve. The analyses confirmed that transient pressures are strongly influenced by the valve operating strategy, with the conventional linear closures producing the highest-pressure surges and pressure deficits. Conversely, the staged valve closure laws considerably reduced both positive and negative pressure extremes, demonstrating that the temporal distribution of the valve movement is as important as the total closure time in mitigating hydraulic transients.

The comparison between the representative operating conditions further highlighted the importance of the initial hydraulic state of the network. Simulations performed under the high-demand condition generated substantially larger pressure surges and more severe structural demands than those obtained during the low-demand period. These results demonstrate that transient risk assessments should not rely on a single steady-state operating condition, since the severity of a transient event depends directly on the hydraulic conditions existing at the moment the disturbance occurs.

A key contribution of the proposed methodology is the transformation of hydraulic transient results into structural performance indicators. Rather than evaluating the network exclusively through transient pressure magnitudes, the proposed methodology converts the governing pressures into circumferential stresses and compares them with material-dependent allowable and resistant stresses. This approach demonstrated that the pipelines experiencing the highest transient pressures or even the largest hoop stresses are not necessarily those exhibiting the greatest structural vulnerability. Instead, pipeline vulnerability depends on the combined influence of hydraulic loading, pipe geometry and material properties, allowing structurally critical pipelines to be identified more reliably.

Finally, the results demonstrate that integrating hydraulic modelling, structural assessment and spatial analysis provide a valuable decision-support tool for water utility management. The generated vulnerability maps allow engineers to identify the portions of the network most susceptible to transient-induced damage and to evaluate the effectiveness of alternative valve operating strategies before their implementation. Consequently, the proposed methodology represents a practical and transferable framework for supporting operation, maintenance and rehabilitation planning in water distribution systems exposed to hydraulic transients.

6.2 Practical Implications

The methodology proposed in this research has direct practical applications for the planning, operation and management of water distribution systems. By integrating hydraulic transient simulations with structural performance indicators, it provides a systematic framework for identifying pipelines that are more susceptible to transient-induced damage and for prioritizing engineering interventions based on objective technical criteria.

One immediate application of the methodology is the evaluation of alternative valve operating strategies. The results demonstrated that modifying the valve closure law can significantly reduce both transient pressures and structural demand without requiring physical modifications to the network infrastructure. Consequently, optimized valve operating procedures may represent a cost-effective mitigation measure capable of improving network reliability while minimizing operational risks.

The proposed workflow also supports asset management by identifying those pipelines that experience the highest structural demand under transient loading conditions. Rather than relying exclusively on pressure magnitudes, the methodology considers the combined effects of hydraulic loading, pipe geometry and material properties, allowing maintenance and rehabilitation priorities to be established according to the actual structural vulnerability of the network.

Another important application concerns the use of GIS-based vulnerability maps as decision-support tools. The spatial representation of hydraulic and structural indicators enables engineers and utility operators to rapidly identify critical sectors of the network, facilitating inspection planning, preventive maintenance and the evaluation of operational scenarios. Furthermore, the methodology allows different valve operation strategies to be compared visually, providing an intuitive basis for selecting safer operational procedures.

Although the methodology was developed using a specific case study, its implementation relies on widely available hydraulic models and open-source computational tools. Consequently, the proposed workflow can be adapted to other water distribution networks provided that an adequately calibrated hydraulic model and basic pipeline information are available. This makes the methodology suitable not only for research purposes but also as a practical engineering tool for supporting operational planning and infrastructure management.

From an engineering perspective, the proposed methodology demonstrates how transient hydraulic simulations can be transformed into practical information for infrastructure management, thereby bridging the gap between hydraulic analysis and asset management within water distribution systems.

6.3 Limitations of the Study

Although the proposed methodology provides a practical framework for evaluating the hydraulic and structural effects of transient events in water distribution networks, several limitations should be acknowledged when interpreting the results.

First, the structural assessment is based on representative allowable and resistant stress values obtained from the technical literature for each pipe material. In practice, the mechanical properties of individual pipelines may vary depending on factors such as manufacturing specifications, installation conditions, ageing, deterioration and previous loading history. Therefore, the calculated stress utilization ratios should be interpreted as comparative vulnerability indicators rather than as definitive measures of structural failure.

Second, the transient analyses considered valve closure events as the only source of hydraulic disturbances. Although valve operations represent one of the most common causes of hydraulic transients, other events such as pump start-up and shutdown, power failures, rapid demand variations or air pocket dynamics may generate different transient responses that were not investigated within the scope of this research.

Another limitation concerns the hydraulic model itself. The transient simulations were performed using a calibrated steady-state hydraulic model and assumed constant pipe characteristics throughout the analysis. Potential changes associated with pipe deterioration, roughness evolution, leakage conditions or future modifications of the network were not considered and may influence the transient response under real operating conditions.

Finally, the vulnerability assessment was developed for a specific water distribution network. Although the proposed workflow is transferable to other systems, the quantitative results obtained in this study should not be generalized directly to networks with different hydraulic characteristics, operational practices or material compositions without performing a new transient analysis.

Rather than reducing the value of the proposed methodology, these limitations define its current scope of application and provide a foundation for future developments aimed at improving the representation of hydraulic transients and structural vulnerability in water distribution systems.

6.4 Recommendations for Future Research

The methodology developed in this research provides a solid basis for further investigations on hydraulic transients and pipeline vulnerability in water distribution systems. Several aspects could be explored in future studies to extend its applicability and improve the representation of transient behavior under real operating conditions.

The first area of future research involves the incorporation of additional transient-generating events beyond valve closure operations. The analysis of pump start-up and shutdown, power failures, emergency operating conditions and combined transient scenarios would provide a more comprehensive assessment of the hydraulic risks affecting water distribution systems.

Further developments could also include the incorporation of pipe ageing and deterioration models into the structural assessment. Rather than considering representative material properties, future methodologies could account for the progressive degradation of mechanical resistance caused by corrosion, material fatigue or long-term service conditions, allowing vulnerability evaluations to better represent the actual condition of existing infrastructure.

An additional line of research would be the validation of the proposed vulnerability assessment using historical records of pipe failures or field measurements. Comparing the predicted critical locations with observed failures would provide valuable information for calibrating the structural assessment criteria and further improving the reliability of the proposed methodology.

Another promising extension concerns the integration of optimization techniques for valve operation. Since the present study demonstrated the significant influence of valve closure laws on transient pressures, optimization algorithms could be employed to automatically determine valve operating strategies that minimize hydraulic and structural demands while satisfying operational constraints.

Finally, the methodology could be extended through its application to different water distribution systems with varying hydraulic characteristics, network topologies and material compositions. Such comparative studies would contribute to validating the robustness and general applicability of the proposed framework, while also providing additional guidance for the development of generalized vulnerability assessment procedures.

Overall, the methodology presented in this research establishes a foundation for future studies aimed at integrating hydraulic transient modelling, structural assessment and asset management into unified decision-support tools for the operation and maintenance of water distribution systems.

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