

Model for improving the operational management of a water supply system

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Resumo

A água destinada a abastecimento público requer uma gestão racional, uma vez que é um recurso escasso e essencial para o desenvolvimento económico e social. Para o consumo humano, podemos afirmar que a matéria-prima é a água doce, recurso que necessita de um conjunto de operações complexas que envolvem a captação, o tratamento e o transporte através de redes de adução e distribuição. Estas operações implicam custos elevados e têm lugar no interior dos designados sistemas de abastecimento público.

Esta dissertação descreve, explica e justifica o trabalho realizado na Águas do Douro e Paiva S.A. pelo aluno para a conclusão do mestrado em engenharia mecânica com especialização em Fluidos e Energia. Trabalho que se debruçou sobre uma componente específica dos sistemas de abastecimento – a gestão de uma rede de adução “em alta”.

Uma componente essencial deste relatório foi modelar e caracterizar adequadamente um componente fundamental de um sistema de abastecimento de água potável - e o objetivo final o desenvolvimento de uma ferramenta capaz de sinalizar corretamente eventos “não-conformes” do sistema, de forma a distinguir e apontar potenciais problemas e ameaças ao seu regular funcionamento. Com esta informação, as entidades decisoras e os responsáveis pela gestão e manutenção da rede têm nas suas mãos dados que ajudam a monitorizar melhor a rede e, também, uma ferramenta que contribuirá para melhorar as suas decisões – quer no que respeita à operação diária, quer sobre a melhor forma de afetar os seus investimentos. Se for bem-sucedido, este modelo pode tornar-se não apenas numa ferramenta, mas num importante ativo de uma entidade gestora a ser partilhado por outras congéneres do setor da água em Portugal.

Após a modelação de uma subsecção de uma rede de água que alimenta vários concelhos do distrito do Porto, foram realizados vários testes de campo com a equipa operacional da empresa para melhor compreender os efeitos que uma anomalia – em particular as variações e flutuações de caudal e pressão - têm na rede de adução. Se corretamente executado, um sistema online enviará um alerta ao gestor operacional, reduzindo significativamente o tempo necessário para que a entidade gestora tenha conhecimento da anomalia, designadamente, a fuga de água numa conduta.

A estratégia de gestão operacional das infraestruturas hidráulicas concebida para este sistema específico visa aumentar a qualidade e a fiabilidade do serviço, reduzir os custos de exploração, mitigar os riscos civis, diminuir as emissões de gases com efeito de estufa (Nexus Água-Energia), melhorar a eficiência energética e conservar um recurso natural universal vital.

Model for Improving the Operational Management of a Water Supply System

Abstract

The water intended for public supply requires rational management since it is a scarce and essential resource for economic and social development. For human consumption, we can state that the raw material is freshwater, a resource that requires a set of complex operations involving capture, treatment, and transportation through supply and distribution networks. These operations involve high costs and take place within the so-called public supply systems.

This dissertation describes, explains, and justifies the work carried out at Águas do Douro e Paiva S.A. by the author for the completion of the master's degree in mechanical engineering with a specialization in Fluids and Energy. The work focused on a specific component of supply systems – the management of a "high-pressure" conveyance network.

An essential component of this report was to model and characterize a fundamental element of a potable water supply system adequately. The ultimate goal was to develop a tool capable of accurately signaling system "non-conformity" events, distinguishing and pinpointing potential issues and threats to its regular operation. With this information, decision-making entities and those responsible for network management and maintenance have data at their disposal to better monitor the network and a tool that will contribute to improving their decisions—both regarding daily operations and the optimal allocation of investments. If successful, this model can become not only a tool but also an important asset for a management entity to be shared among other counterparts in the water sector in Portugal.

After modeling a subsection of a water network that supplies several municipalities in the Porto district, several field tests were conducted with the company's operational team to better understand the effects that an anomaly—specifically flow and pressure variations and fluctuations—has on the conveyance network. If properly executed, an online system will send an alert to the operational manager, significantly reducing the time it takes for the management entity to be aware of the anomaly, specifically a water leak in a pipeline.

The operational management strategy of hydraulic infrastructures designed for this specific system aims to increase service quality and reliability, reduce operating costs, mitigate civil risks, offset greenhouse gas emissions (Water-Energy Nexus), improve energy efficiency, and conserve a vital universal natural resource.

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Acronyms

AdDP – Águas do Douro e Paiva, SA

PE – Pontos de entrega (delivery points)

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1 Introduction

Water stands out as a critical natural resource, unlike others, given its pivotal role in advancing and sustaining societies. Its significance in the establishment, operation, and growth of communities underscores its unmatched importance. Acknowledging water as an indispensable natural resource and prioritizing its preservation is a vital move to secure it as a universal right. Effecting a shift in the mindset regarding water consumption and diverse uses necessitates a resolute commitment from responsible entities. This commitment should be evident in both legal frameworks and management strategies.

Water supply systems are crucial for the well-being and convenience of the communities they cater to. In Portugal, significant investments have been directed towards establishing these infrastructures in the past two decades, and their ongoing upkeep will inevitably demand substantial financial resources and human efforts. The significance of these systems is often underestimated by the average consumer, as a considerable portion of the population tends to assume the continuous provision of high-quality service. This underestimation can be attributed to various factors, including the predominantly underground nature of these infrastructures and the ingrained expectation of access to clean and safe water without restrictions for daily needs.

In a situation where urban areas are well-established and constitute either entirely or partly a segment of an infrastructure, a new approach to the supervision of hydraulic systems, their renovation, and adaptation is noticeable. The recognition of the lifespan of networks and emerging requirements serves as the impetus for this innovative stage in the management of hydraulic infrastructure (Brandão 2011). Progress in technology facilitates the automated monitoring of consumption linked to various segments of the network. The incorporation of real data in the planning and operation of supply system infrastructures can signify a pivotal advancement towards achieving systems that are more effective. (Gonçalves (2014))

The access to a substantial volume of data by management entities, supported by advanced computer tools for processing and organization, along with modeling software that integrates this data, has the potential to facilitate the simulation of crucial scenarios for system exploration. Tools like real-time control and analysis of how water distribution networks respond to varied demands offer the means to optimize operational management. Within the field of engineering, opting for real data instead of hypothetical data may serve as a route that brings theoretical approaches closer to the actuality of systems. This choice can serve as an initial step for deliberations on the foundational data crucial in various projects, including the establishment of new systems, their rehabilitation, and modification, encompassing aspects like determining the life and return periods assigned to each component of the system.

1.1 Project Framework and Motivation

This dissertation's subject came as a proposal from Águas do Douro e Paiva (AdDP) Company, more specifically from the department responsible for the management of a water supply system that feeds Greater Porto. AdDP must reach demanding objectives while absorbing the least possible amount of resources (financial, human, chemical) and energy, always striving for the highest levels of efficiency. While electrical and hydraulic energy might be considered the primary energy vectors in the water treatment and supply sector, it's important not to overlook the energy expended in transporting the workforce, their equipment, materials, machines, etc for daily operational and maintenance activities.

Even though this company has other obligations to their clients related to water quality treatment, this thesis will focus only on the supply and distribution department. At the Lever water treatment plant, raw water from Douro River goes through several physical and chemical processes that transform untreated water into potable water. Some of these operations are

pretreatment, pre-disinfection, coagulation, dosing of activated carbon powder, flotation, filtration, disinfection, sludge or mud treatment and final quality control in a specialized lab.

A new challenge will face AdDP in the near future as the infrastructure and assets that they are responsible for (some of them inherited from other entities, mainly municipalities) approach the conclusion of their operational lifespan. Whether these are ducts, fittings, valves, reservoirs, pumps, motors, sensors, etc., any equipment has a lifetime. While several of these components are not inherently challenging to replace or repair, when it comes to the aging of hundreds of kilometers of underground ducts the case is much different. These elements are very hard to access, oftentimes needing to close down roads for days, requiring heavy machinery, specialized work, and also sometimes older pipes may use outdated materials or construction methods that are no longer standard.

A second issue to consider is the desertification of some areas of Portugal that will lead to water scarcity. In Portugal, there are some discussions regarding the possibility of transporting water from the north to areas affected most by climate change. There are several technical solutions to address this issue like water transfer from areas with higher water availability or, for instance, desalination plants. Whatever the case may be, the main focus and priority is water efficiency. So, we can summarize the motives for this thesis theme:

- Improve operational management and the detection of anomalies in the system's operation.
- Increase knowledge of how AdDP's system works in the face of different events.
- Focus on water efficiency and water loss reduction.
- Start an operational journey towards more intelligent, sensor-based, and data-centered management.
- Improving AdDP's technological advancement aiding everyday working routines.
- Digitalization of operations.

1.2 Águas do Douro e Paiva Company

Águas do Douro e Paiva, S.A. is a public limited company with exclusively public capital, established by Decree-Law 16/2017, dated February 1st. It is responsible for the conception, construction, and management of the multi-municipal supply system in the southern region of Greater Porto, under an exclusive regime and for a period of 20 years. AdDP (2024)

This company stems from the division of the multi-municipal water supply and sanitation system in Northern Portugal, resulting from the aggregation of systems created by Decree-Law No. 93/2015, dated May 29.

The company's objective is to capture, treat, and supply water for public consumption to 1.7 million residents in the 20 shareholder municipalities, covering an area of 2,715 km².

Figure 1 displays the revised map of the system, providing an overview of the complete influence area of the Multimunicipal Water Supply System, specifically focusing on the southern region of Greater Porto.

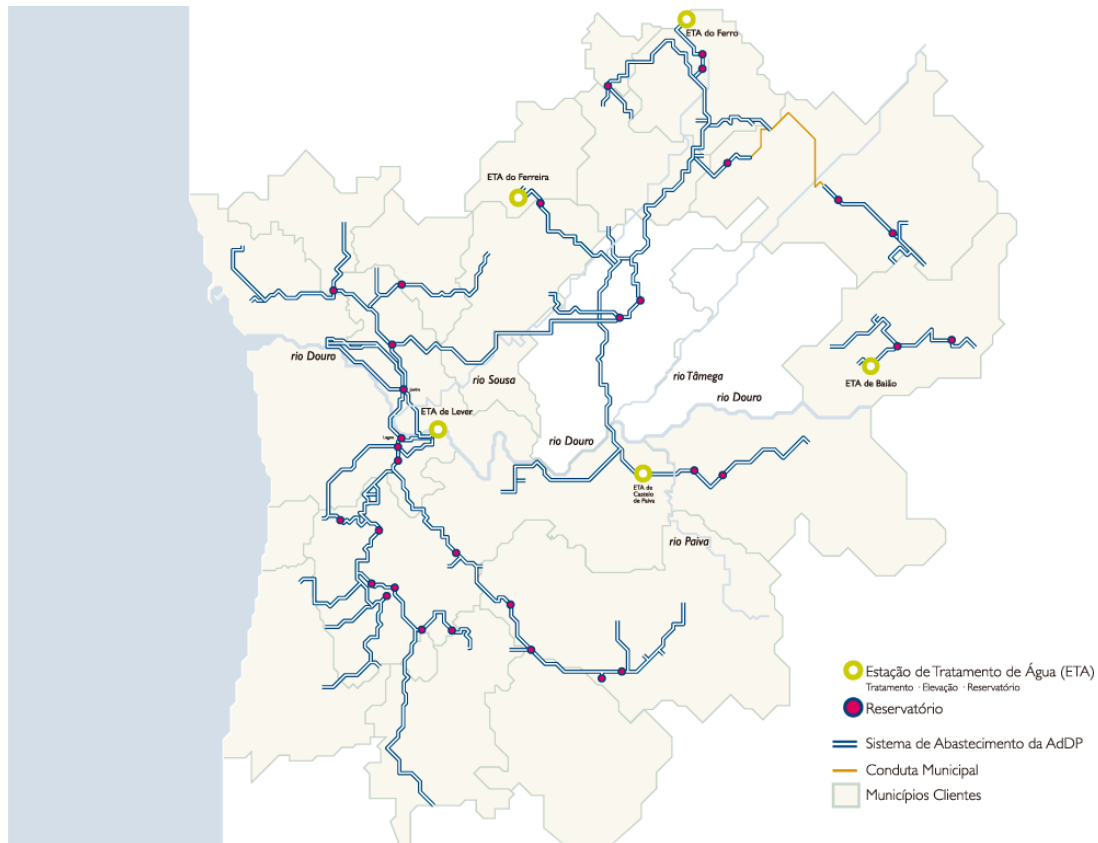


Figure 1 - AdDP Network Map

According to the concession established by law, the company is constituted by Águas de Portugal, SGPS, S.A., holding 51% of the share capital, and the municipalities of Amarante, Arouca, Baião, Castelo de Paiva, Cinfães, Espinho, Felgueiras, Gondomar, Lousada, Maia, Matosinhos, Oliveira de Azeméis, Ovar, Paços de Ferreira, Paredes, Porto, Santa Maria da Feira, São João da Madeira, Valongo, and Vila Nova de Gaia, holding the remaining 49%. AdDP (2024)

1.2.1 Vision, Mission, and Corporate Responsibility Policy

Vision

“To be recognized for our efficiency, competence, sustainability, and value creation for the region.”

Mission

“To manage the high-pressure water supply system, ensuring efficiency, reliability, service quality, product safety, and respect for the highest social and environmental values.”

Corporate Responsibility Policy

“Aguas do Douro e Paiva (AdDP), committing to actively contribute to the sustainable development of water supply services and the achievement of national goals set for the sector, is dedicated to fulfilling social obligations and responsibilities towards shareholders, customers, employees, the grantor, suppliers, community, and other stakeholders.”

“Aware of its role as an instrument for socio-economic development in the region, the company also undertakes the promotion of environmental protection and its appreciation within the community.”

“In this context, AdDP applies a business strategy based on the following principles:

- Client satisfaction*
- Employee motivation*
- Process efficiency*
- Continuous Improvement and Innovation*
- Transparency and Communication”*

1.2.2 High pressure System

The high pressure (*"em alta"*) component of a water supply system encompasses all stages from the raw water intake, its treatment and transportation to the supply networks of treated water to the "low pressure" component for future distribution to consumers. Thus, this component consists of water intake points, water treatment plants, reservoirs, pumping stations, chlorination stations and mains.

In the case of Porto, the high pressure component is managed by AdDP, as the water required for the city's supply is purchased by Águas do Porto. This entity, which is responsible for the low pressure network management (the *"em baixa"* component), stores and distributes water to the final users as AdDP provides it already treated, ready for use. Oliveira (2013)

1.2.3 Low pressure System

The downstream segment of a water supply system, known as the low pressure component, encompasses the journey of treated water from its supply by the high pressure component through the primary feeder pipe to its distribution to end users via the distribution network. It includes distribution reservoirs, pumping stations, feeder pipes operating under gravity or elevation, the distribution network itself, and ultimately, the household delivery branches.

The supply of water from the *"em alta"* component can be done in two ways. Ideally, the water should be delivered to the low pressure entity reservoirs through delivery points (*Pontos de Entrega* (PE)) from the feeder pipe at these elements. However, a second way is to deliver directly from the high pressure feeder pipe to the downstream distribution networks. In the case of Porto, both methods are used, maximizing the benefits of local topography and the deployed distribution network. (Oliveira (2013))

1.3 Objectives

This dissertation's ultimate goal is to improve the Operational Management of potable water supply infrastructure assets. The strategy chosen was to model part of a hydraulic system only by knowing and using the real time data available by the management entity, specifically operational data (flow rates and system pressures). With the expertise learned through fluid mechanics courses in mechanical engineering, a water distribution system will be characterized to understand its conditions in a normal state of operation. If successful, the management entity will be warned preemptively if the water network is performing outside its expected conditions.

Additionally, this report sought to better understand the pressure and flow fluctuations that occur in an anomalous event, so several field tests were conducted at various points of the network. These experiments intend to simulate a leak that can occur in a hydraulic system and after completion, the internal remote management records the data to analyze the results. The real values and the ones from the model are compared in order to validate the chosen methodology and understand its limitations.

1.4 Work method followed in the project

The work carried out over 6 months in Águas do Douro e Paiva is best simplified in the timetable in Figure 2 below:

month	set			oct				nov					dec				jan				feb	
weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Learning the water sector / Group Águas de Portugal																						
Knowledge of the various areas of the company																						
Knowledge of on-site infrastructures																						
Literature review																						
Knowledge of equipment relevant to the development of the dissertation																						
Knowledge of the company's operating systems and operating mode																						
Methodology development																						
Modeling the network																						
Application to the case study																						
Development of the thesis																						

Figure 2 - Semester schedule

1.5 Dissertation Structure

This report is divided into 5 chapters, which are briefly described below.

This first chapter provides an initial approach to the subject under study, a brief presentation of the host organization and a description of the objectives the author set himself during his work.

The second chapter presents a more in-depth look at water losses, defining it from a administrative perspective and then through a more technical lens. In it are presented the causes, consequences, and some prevention methods.

The third chapter delves into monitorization and control, trying to discover and understand the evolution of different technologies that describe, in real time, the updated state of the system in normal operation.

The fourth chapter explains the methodology used to model the water network, using fluid mechanics equations studied in mechanical engineering and a simulation software used for water supply systems.

The fifth chapter describes the experimental tests conducted, simulating an abnormality in the system, and correlating it to changes in the operational data.

The last chapter presents the final conclusions of this thesis and offers some suggestions for future work.

2 Water losses

Water losses are characterized by the variance between the volume of water entering the system and the consumption authorized by the management entity, as stated by Loureiro (2012). The International Water Association (IWA) introduces a vocabulary for water consumption and losses, embodied by the water balance in Table 1.

Table 1 - Components of Water Use in Water Distribution Systems

Water that enters in the system	Authorized consumption	Billed authorized consumption	Billed metered consumption (including exported water)	Revenue Water
			Billed unmetered consumption	
		Unbilled authorized consumption	Unbilled Metered consumption	Non-Revenue Water
			Unbilled unmetered consumption	
	Water losses	Apparent losses	Unauthorized consumption	
			Measurement errors	
		Real losses	Leaks in supply and/or distribution pipes	
			Leaks and overflows in supply and/or distribution reservoirs	
			Leaks in the branches (upstream of the measuring point)	

As per (Alegre et al. 2005) , real losses pertain to the physical water losses up to the meter of each customer, occurring at various junctures within water supply systems such as reservoirs, main pipes, distribution pipes, and service pipes. These losses encompass the volume of water dispersed through leaks, ruptures, or overflows, contingent on the frequency, consumption, and average duration of the leaks. In accordance with the BABE concept (Background and Burts Estimates), real losses can be categorized into three components (Farley and Trow (2005)) :

- Losses due to reported leaks and ruptures
- Losses due to unreported leaks and ruptures
- Background losses

Background losses, identifiable by diminished flows and prolonged duration, are frequently not detectable with commonly used equipment. Breaks are linked to flows surpassing $0.5 \text{ m}^3 / \text{h}$, with varying durations. Alegre et al. (2005); Lambert and Morrison (1996)

Apparent losses signify the volume of water that enters the distribution system and reaches an end user but is not accurately measured and/or billed. It consists of unauthorized consumption,

illicit connections, customer metering inaccuracies, and systematic data handling errors. (Services (2022))

Unauthorized consumption means the volume of water that is taken from the water supply system without the authorization of the water utility. Examples include unpermitted water withdrawals from fire hydrants, illegal connections, bypasses to customer meters, and meter or meter reading equipment tampering.

Unbilled metered consumption refers to the volume of water that has been measured by meters but is not accounted for in billing or revenue collection. This can occur due to various reasons such as meter inaccuracies, data recording errors, or issues in the billing process.

Unbilled unmetered consumption means the volume of authorized consumption that is neither metered nor billed. The most common examples of this consumption are firefighting, flushing, and street cleaning.

Water losses are actually a prevailing aspect in all water supply systems, underscoring that their magnitude is contingent upon various factors such as the characteristics of the supply network, terrain topography, operational practices, level of technology, and applied knowledge. The management of pressures within water supply networks is intricately linked to prolonging the lifespan of pipelines, postponing the occurrence of leaks and ruptures over time, and mitigating pre-existing and challenging-to-detect losses, thereby diminishing the influx of water into the system. The application of mathematical modeling emerges as a valuable tool for simulating the hydraulic behavior of the network, particularly with regard to real losses, facilitating the pinpointing of critical points (e.g., network areas necessitating pressure-related interventions, locations of consumption experiencing excessively high pressures, regions with inadequate pressure), as highlighted by Cardoso (2013).

2.1 Causes

To simplify matters, provided below is an exhaustive list of the main causes of leaks in water network systems:

Duct corrosion: corrosion is a process in which the material of a pipe gradually deteriorates due to chemical reactions with its surroundings. For metal pipes, usually there is a protective layer to protect the iron from the outside environment. With the passage of time, this layer gets thinner, and the humidity comes in contact with the duct, causing oxidation. This compromises the integrity of the duct, weakening it and increasing the likelihood of an orifice emerging or deteriorating it to the point that an exterior force induces a perforation.

Joint failure: To connect two sections of a duct together, the usual technique is for one end to enter a wider section of the other and to use a rubber gasket to create the seal. Due to environmental factors, temperature variations and ageing, the rubber degrades. This is a process in which the physical and chemical properties of rubber materials change over time leading to a decline in its performance and structural integrity. Heat causes rubber molecules to move more rapidly, promoting chemical reactions that contribute to degradation. Conversely, extreme cold temperatures can make rubber more brittle (although not usual in Portugal's climate conditions). Continuous stretching, flexing, and compressing of rubber components can contribute to fatigue and mechanical wear over time. This stress can result in the development of cracks and fractures. Some examples of this type of failure can be seen in Figure 3 and Figure 4.



Figure 3 - Joint Failure



Figure 4 - Joint failure 2

Material Defects: When the equipment comes with defects from the factory. This is a rare event and is usually detected before installation, showing the importance of performing inspections before installing components.

Ground Settlement and Subsidence: Settlement refers to the gradual sinking of the ground, while subsidence is the sudden sinking or caving in of the ground. These processes can occur due to natural geological factors, changes in soil moisture, or human activities. This can put stress on underground pipes, causing them to crack or rupture. This stress may result from the uneven settling of soil around the pipes. These consequences can also be caused by seismic activity and soil erosion (exposed pipes may be more susceptible to damage from external forces, including pressure from shifting soil. Additionally, erosion can create voids around pipes, leading to instability).

Poor Installation: Flawed reception, storage, and installation of equipment and components on site (exposure to weather), inadequate pipe alignment, improper joint sealing, incorrect pipe material selection, insufficient bedding and backfill, inaccurate slope or grading.

Exterior damage: Accidental damage from construction, excavation activities and intensive traffic. Also damage from tree root growth and earthquakes although much rarer.

Poor maintenance: System components must be maintained to ensure their required performance. Regular inspections and monitoring are essential for identifying potential issues before they escalate to something worse. Delayed repairs lead to higher repair costs when the issue is finally addressed. Timely inspections, prompt repairs, and a comprehensive maintenance strategy contribute to the long-term sustainability and performance of the infrastructure.

Ageing infrastructure: With the passage of time, system components no longer perform to their original specifications. Deteriorated joints and seals can allow water to escape, contributing to leaks. The loss of flexibility and sealing effectiveness over time makes these points vulnerable. Older water supply systems may use outdated materials and technologies that are less resilient to wear, pressure changes, and environmental stresses. Sometimes some old parts and components are no longer manufactured which makes for incompatibilities when attempting to make repairs.

Poor conceptual design: Sizing errors (poor forecasting of water consumption or pressure demands, adoption of inappropriate calculation methods and assumptions and calculation errors leads to incorrect diameters, lengths, etc.), poor choice of equipment and materials (joining incompatible equipment, decision on the placement and location of valves), different designers designing different parts, etc.

Change in initial design conditions: As communities grow, the original water supply infrastructure may become inadequate to meet current demands, leading to stress on the system. If the network was initially designed to provide a certain amount of water to a municipality, when there is a change in the population (change in consumption) then the system will operate outside its design conditions of flow and pressure. This leads to a lower lifespan of the entire system, needing to make earlier replacements.

Water hammer: Also known as hydraulic shock, occurs when there is a sudden stop or change in fluid flow within a closed water supply system. This phenomenon is referred to as water hammering because the pressure surges are frequently accompanied by a noise that sounds as if the pipeline were being pounded with a hammer. This can happen due to the opening/closing of valves and also when starting/shutting down pumps. These pressure fluctuations subject the pipes to stress, particularly at bends, joints, and vulnerable points in the system. Over time, this stress can lead to the development of microcracks and weaknesses in the pipe structure.

Temperature fluctuations: Thermal expansion is a physical phenomenon in which a material undergoes dimensional changes in response to variations in temperature. When a substance is heated, its molecules or atoms gain kinetic energy, causing them to move more and occupy a larger volume. Conversely, cooling a material reduces the kinetic energy of its particles, leading to a contraction or decrease in volume. This thermal expansion and contraction create stress on the duct material. Over time, especially with frequent temperature fluctuations, the material experiences fatigue. Duct systems may incorporate multiple materials with different coefficients of thermal expansion. This means that these materials expand and contract at different rates, leading to stress concentrations at material interfaces. This can result in the development of cracks and separation points. This cause is much more usual when ducts are exposed and installed alongside bridges, crossings, and technical galleries.

Cyclical fatigue: Cyclical fatigue induced by pressure variations in water ducts can increase the likelihood of leaks through a process that involves repeated stress and strain on the material of the ducts. Stress is the force applied to the material, and strain is the resulting deformation. The repetitive nature of these stress and strain cycles can lead to cumulative damage over time. Fatigue manifests as microstructural changes, such as the formation of microcracks and dislocations within the material. These changes may not be immediately visible but can accumulate over time. Also, exposed pipes with high velocity of fluid flow may undergo vibratory motions, which may cause fatigue damage in the pipe and its connections. The flutter type instability may also occur in the pipes with high velocity fluid motion. (Farshad (2006))

2.2 Consequences

Water loss: Freshwater is vital for human survival as it is necessary for drinking, cooking, and hygiene. Without an adequate supply of clean water, humans cannot survive for more than a few days. It is indispensable for agriculture and food production, used for irrigation, livestock watering, and crop cultivation.

Financial costs: The biggest financial expense of AdDP is the cost of electrical energy needed for the collection, treatment, transportation, and distribution of water. Any water loss means a waste of funds that could be better used for modernizing existing equipment, training their human resources, or even simply lowering the absolute amount of financial expenditure, possibly lowering the costs for their clients.

Pressure loss: One of the main objectives of this dissertation is to determine the pressure loss in the network in the event of a leak. Lower pressure means inadequate service delivery, especially in higher elevation areas or during peak demand periods.

Water Quality Degradation: Leaks can allow contaminants to enter the water supply system, compromising water quality and posing health risks to consumers. At several points in the system, chlorine is added to the water. Chlorination is the process of adding chlorine to drinking water to kill parasites, bacteria, and viruses. If impurities and pollutants enter the system, the treatment process has been squandered.

Infrastructure damage: The structural integrity of buildings, bridges, roads, foundations, etc. It can lead to erosion, corrosion of steel reinforcements, and degradation of building materials such as wood, concrete, and masonry.

Risk to life: some leaks start small and evolve over time, beginning to “excavate” the ground below civil roads (a big proportion of the network follows the path of public roads). The

loss of support leads to a significant cave ins as illustrated in Figure 5. As we can see, these catastrophic events can lead to serious injuries and sometimes even death.



Figure 5 - Road Cave in

Hydraulic efficiency degradation: If a pumping station is situated on a system with constant leaks this means that, in order to supply the same volume to each point, it will have to operate outside its design conditions of flow and pressure. Considering that pumps have a specific range where they are at their most efficient, functioning outside of these bounds signifies consuming more energy for the same output, which implies more financial losses and higher greenhouse gas emissions.

Energy and Greenhouse gas emissions: As mentioned previously, all the processes to transform untreated water and transport potable water requires significant amounts of energy, but we cannot forget the expenditure in identifying, locating, repairing, and repairing the ducts, valves, equipment, roads, sidewalks, and other infrastructure that was affected. All these elements have a carbon footprint associated with its manufacturing and transportation (mostly energy derived from fossil fuels) to the compromised area that must be taken into account. Additionally, if the water from leaks infiltrates the drainage and sanitation systems, it is a higher amount that reaches waste water treatment plants and sanitation pumping stations. This signifies more energy consumption for treatment and pumping.

The production of energy is associated with the release of greenhouse gas emissions that depend on each country's energy mix. As we already know, this increase contributes to the ongoing climate change that affects life on the planet.

2.3 Prevention

Preventing water leaks in large water supply systems requires a multifaceted approach involving various strategies and technologies. Here are several ways for prevention:

Using modeling strategies: This is the main focus of this dissertation, to use mathematical modeling to identify leaks and prevent their growth in water supply systems before they grow to become safety hazards by modeling the hydraulic behavior of the network.

Regular inspections: Implement routine inspections of pipelines, valves, fittings, and other components to detect and address potential leaks promptly.

Pressure Management: Optimize water pressure levels in the distribution network to minimize stress on pipelines and reduce the likelihood of pressure spikes. During their daily tasks, the monitoring and control technicians in the command center have some responsibilities like opening and closing valves and shutting down and turning on pumping stations. There is a big difference in the resulting pressure variation depending on the speed that these components open and close. As can be seen in Figure 6, the rapid closure and opening of valves results in major fluctuations of pressure on the entire network. This goes back to what was said in Chapter 2.2, where pressure peaks and pressure fatigue are one of main reasons for the creation of a fissure. So, another approach to prevent this problem is to create standard opening and closure rates for these assets, resulting in a smoother change in network pressure and flow.



Figure 6 - Telemetry Data for pressure

Infrastructure Rehabilitation: Invest in the rehabilitation, replacement, and modernization of aging water supply infrastructure to address systemic issues and reduce the risk of leaks. This is the main goal of the asset management approach which refers to the systematic process of acquiring, operating, maintaining, upgrading, and disposing of assets in a cost-effective manner. It involves managing an organization's physical assets (such as equipment, machinery, infrastructure, and properties) to maximize their value and performance throughout their lifecycle. Asset management optimizes the use of resources, reduces risks, ensures compliance with regulations, and supports the organization's objectives and strategic

goals. It typically involves various activities such as asset inventory, condition assessment, maintenance planning, risk management, and decision-making based on data-driven insights.

Some examples of infrastructure rehabilitation for a water company include: implementing pipe relining, pipe bursting, and trenchless technologies to minimize disruption and extend the service life of pipelines.

Public Awareness and Education: Educate the public, water consumers, and stakeholders about water conservation practices, leak detection tips, and reporting procedures. Encourage water-saving behaviors, promote leak detection awareness campaigns, and provide resources for leak repairs and water efficiency upgrades.

By implementing these preventive measures and adopting a proactive approach to water management, large water supply systems can minimize the occurrence of leaks, conserve water resources, and ensure the reliability and sustainability of water supply services for communities and industries.

3 Telemetry and Telemanagement

In the execution of the distribution networks, AdDP installed a fiber optic network along the entire length of the 500 km network. This network was used as a data transmission system for remote management and at the same time utilized as a voice and image communication network.

The Telemetry System uses computing and communication technologies to control all processes of water production for human consumption, collecting data from geographically dispersed facilities, and presenting it in a timely and user-friendly manner at the Command Center as can be seen in Figure 7. This includes all information (analyses, graphs, and reports) necessary for making operational decisions consistent with the current state of the system.

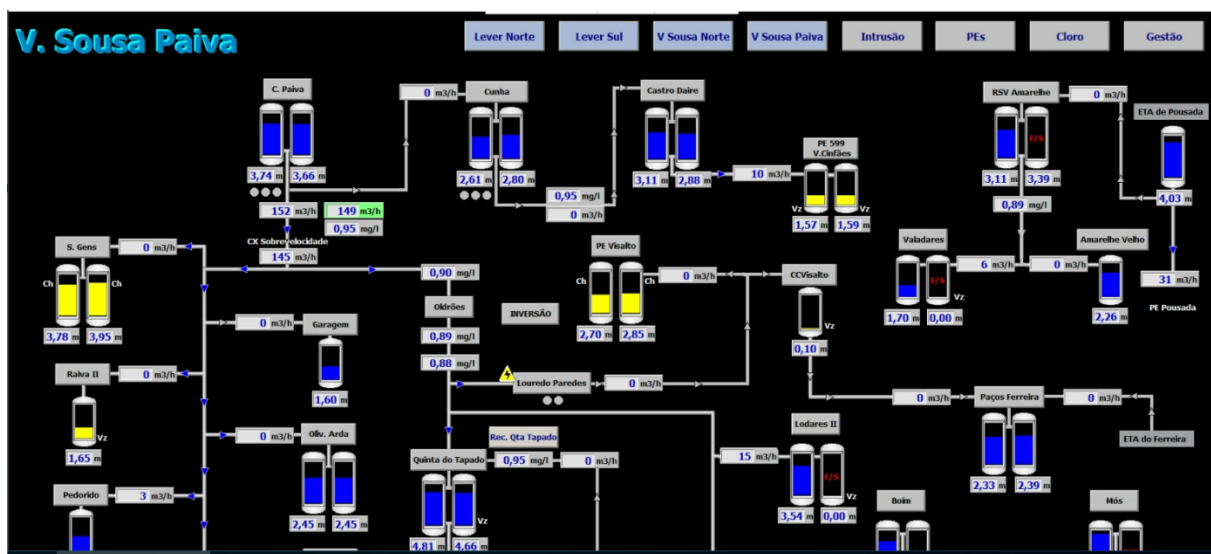


Figure 7 - Telemangement Interface

Consisting of an architecture with three levels (decision, communication, and acquisition/control), the system incorporates a set of equipment adapted with autonomous processing capabilities. These devices perform the acquisition of controlled variables and ensure surveillance and security of the facilities by constantly comparing reference values with actual physical and chemical variables. When critical values are reached, automatic corrections are made, which may involve modifying the state and/or position of final components.

The advantages of its use are numerous as it improves the overall quality of the service provided, allowing for:

- Safety in network operation, as technicians are alerted to all anomalies – reservoir levels, pressure drops, power outages, equipment failures – enabling immediate alternatives to be found based on the severity of the reported problems.
- Technical management through real-time processing of information collected from installations, with the possibility of intervening in the operation of all control components (pumping groups, valve states, reservoir levels, chlorometers, circuit breakers, and others).
- This automation reduces the need for human resources, with faster response times. Human resources can focus on more important responsibilities

- Management of electrical energy for all pumping and treatment installations, through the implementation of automations that correlate the energy tariff with reserved volumes.
- Quality control by real-time verification of water quality parameters.
- Statistical management through data storage that is edited in the form of balances or statistics of operation to improve technical and economic conditions, ensuring the quality and quantity of distributed water.

Automatic readings not only play a crucial role in the installation of the counting system but also generate valuable information for the management entity regarding customer consumption patterns, indicating the direction and distribution of water as depicted in Figure 8. This contributes to more efficient network management. The advantages of automatic readings include cost reduction through streamlined data collection and enhanced resource management, which can be redirected to new initiatives. Providing data through an online portal accessible to consumers may foster a proactive approach to water consumption management. The generated information enables more frequent efficiency assessments of systems and the implementation of more effective methodologies for monitoring and control, as highlighted by Malheiro (2011).

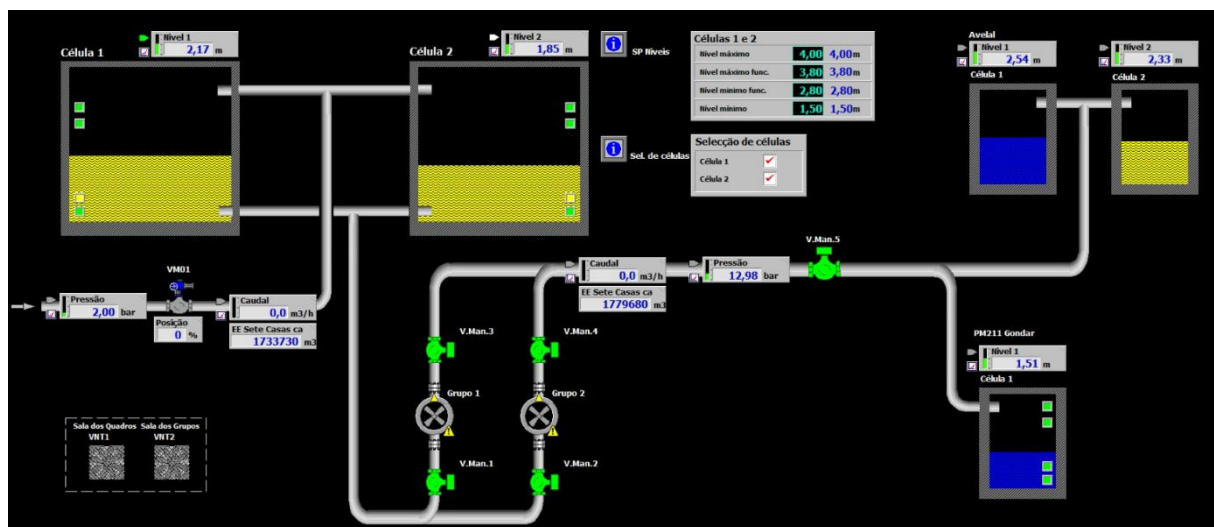


Figure 8 - Interface with reservoir levels

4 Modeling the supply network

Mathematical modeling is a fundamental tool used across various disciplines to represent, analyze, and understand complex systems and phenomena using mathematical equations, algorithms, and computational techniques. At its core, mathematical modeling involves formulating a mathematical representation of real-world processes or systems to gain insights, make predictions, and solve problems.

A mathematical model is a simplification of a problem to a small system of equations, which capture the essential essence of it, and, crucially, are simple enough to allow us to make analytical calculations. A formula derived from an analytical calculation can give a clear view of the role of the parameters in that system without having to run a very large number of calculations. Ribeiro (2016)

There are many strategies to identify leaks in a network but for this dissertation the challenge in particular was to create a model that only uses the real time operational data from pressure sensors and flow meters that are installed throughout the network.

The strategy preferred for this specific problem with its specific requirements was to model the network using fluid mechanics equations that describe the relationship between all the different attributes that define a system comprised of fluids in motion. With this, it predicts what is the expected pressure for each node in the duct network assuming that there are no leaks. After estimating those values, it compares them with the existing pressure sensors that are physically connected to the network. An alert will be sent to the operational manager responsible for the system of the possibility of existing an abnormality in a sector defined by the connection between two nodes. This method won't precisely discover the area of the irregularity, the shorter the distance between two nodes the faster it will be located.

4.1 Bernoulli equation

Daniel Bernoulli, a Swiss mathematician, introduced the principle of conservation of energy to fluid dynamics in the 18th century. In his book "*Hydrodynamica*," published in 1738, he presented the fundamental concept that would later become known as the Bernoulli equation. Bernoulli's work laid the foundation for understanding fluid flow and its applications in various fields.

The Bernoulli equation is based on the principle of conservation of energy and states that the total mechanical energy per unit mass of a fluid remains constant along a streamline. It comprises three main components:

Pressure Energy (P): Represents the energy associated with the pressure of a fluid. This energy arises from the force exerted by the fluid on its surroundings due to molecular collisions. Pressure energy can be converted into other forms of energy, such as kinetic energy or potential energy, depending on the fluid's motion and the presence of external forces. For instance, when fluid flows through a nozzle, the pressure energy can be converted into kinetic energy, leading to an increase in fluid velocity.

Kinetic Energy: represents the energy associated with the motion of a fluid. Kinetic energy increases quadratically with the velocity of the fluid particle. This means that doubling the velocity of the fluid particle results in a fourfold increase in kinetic energy.

Potential energy: Potential energy is the energy associated with the elevation of the fluid above a reference point. It depends on the gravitational acceleration and the height of the fluid above the reference point.

The equation can be expressed as:

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho gh_1 = \text{const} \quad 4.1$$

Where:

- P is the pressure of the fluid;
- ρ is the density of the fluid;
- v is the velocity of the fluid;
- g is the acceleration due to gravity;
- h is the elevation of the fluid.

While the Bernoulli equation provides valuable insights into fluid behavior, it has several limitations:

- It assumes ideal conditions, such as steady, incompressible, and frictionless flow, which may not hold true in real-world scenarios.
- The equation does not account for factors such as viscosity, turbulence, and external forces.
- It applies strictly to inviscid flow, where viscous effects are negligible. In viscous flows, modifications or additional equations are necessary to account for viscosity.

Fluids lose energy as they flow through pipes due to several factors, including frictional losses, and losses associated with fittings and components (localized losses) within the pipeline.

Frictional losses in pipes means a fluid loses energy to friction as it encounters resistance opposite the flow direction. This resistance converts the fluid's mechanical energy into heat, resulting in a decrease in the fluid's total energy along the length of the pipe. Frictional losses arise due to the interaction between the fluid molecules and the pipe wall as the fluid flows. The irregularities on the pipe wall create turbulent flow patterns within the fluid, dissipating energy in the form of heat.

Pipes often contain various fittings, such as elbows, valves, tees, and reducers, which disrupt the smooth flow of the fluid. As the fluid passes through these fittings, it undergoes changes in velocity, direction, and pressure, resulting in energy losses due to turbulence and vortices generated by the flow disturbances. These are called localized losses.

Considering a closed system of fluid motion, the total energy transfer with the outside environment will be due to these frictional and localized losses. As shown in Eq. 4.2, the total energy of the fluid at a point further downstream will be the initial energy minus the energy lost to friction and fittings.

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho gh_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho gh_2 + \text{Losses} \quad 4.2$$

The question arises then, how to properly calculate these losses.

4.2 Darcy-Weisbach Equation

Energy losses in fluid flow, particularly frictional losses, can be calculated using various empirical equations and principles of fluid mechanics.

The Darcy-Weisbach Equation is a fundamental equation in fluid mechanics used to calculate head loss due to friction in a pipe. It is named after Henry Darcy, a French engineer, and Julius Weisbach, a German engineer, who independently developed similar equations in the mid-19th century. The equation relates the pressure loss in a pipe to various parameters:

$$h_f = f \frac{L}{D} \frac{v^2}{2g} \quad 4.3$$

- h_f = head loss due to friction (*mca*)
- f = Darcy-Weisbach friction factor (dimensionless)
- L = Length of the pipe (*m*)
- D = Diameter of the pipe (*m*)
- v = Velocity of the fluid (*m/s*)
- g = Acceleration due to gravity (*m / s²*)

The Darcy-Weisbach friction factor is a dimensionless quantity used in fluid mechanics to characterize the amount of frictional resistance experienced by a fluid as it flows through a pipe or conduit. It is a fundamental parameter in the Darcy-Weisbach equation, which relates pressure loss to flow rate, pipe diameter, length, and fluid properties.

The Darcy-Weisbach friction factor takes into account the roughness of the pipe wall, the Reynolds number of the flow, and other factors that influence the flow regime. It is commonly used in both laminar and turbulent flow conditions, although its calculation methods differ for each regime.

In laminar flow (characterized by low Reynolds numbers), the friction factor can be calculated using the Poiseuille equation, which describes flow in smooth pipes:

$$f = \frac{64}{Re} \quad 4.4$$

4.3 Colebrook-White equation

In turbulent flow (characterized by high Reynolds numbers), the calculation of the friction factor is more complex and often requires empirical correlations or experimental data. The most widely used correlation for turbulent flow is the Colebrook-White equation:

$$\frac{1}{\sqrt{f}} = -2 \log \left[\frac{\frac{\varepsilon}{D}}{3,7} + \frac{2,51}{Re\sqrt{f}} \right] \quad 4.5$$

Where:

- f is the Darcy-Weisbach friction factor
- Re is the Reynolds number (dimensionless)
- ε is the absolute roughness of the pipe wall
- D is the diameter of the pipe

The Darcy-Weisbach friction factor can be determined using empirical correlations, experimental data, or obtained from friction charts. For laminar flow ($Re < 2000$), the friction factor is constant and can be calculated analytically. For turbulent flow ($Re > 4000$), the friction factor depends on the Reynolds number and relative roughness and is typically determined using empirical formulas or Moody charts.

For this model, an iterative method was used where we plug in a starting value for the friction factor to obtain a new value of f . This method leads to a convergence as depicted in Figure 9, whose values for Reynolds number, absolute roughness and diameter were used from a normal duct belonging to the Vale do Sousa Norte subsystem. The iteration is stopped when the difference between the new value and the previous is negligible. The starting value often used is 0,02.

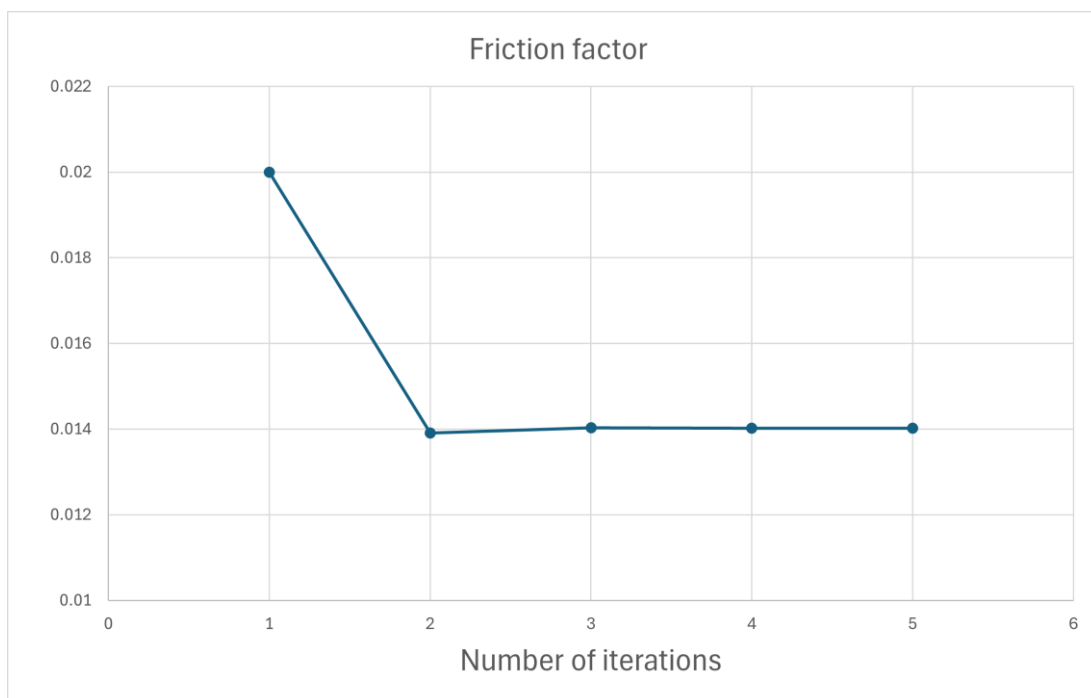


Figure 9 - Number of iterations with friction factor

As we can notice, the number of iterations necessary to reach convergence is low, making this repetitive method very simple and quick to calculate.

When performing the calculations to determine energy loss per unit of length of a duct, an important relationship is observed. As illustrated in Figure 10, the pressure drop varies exponentially with the fluid velocity within the conduit.

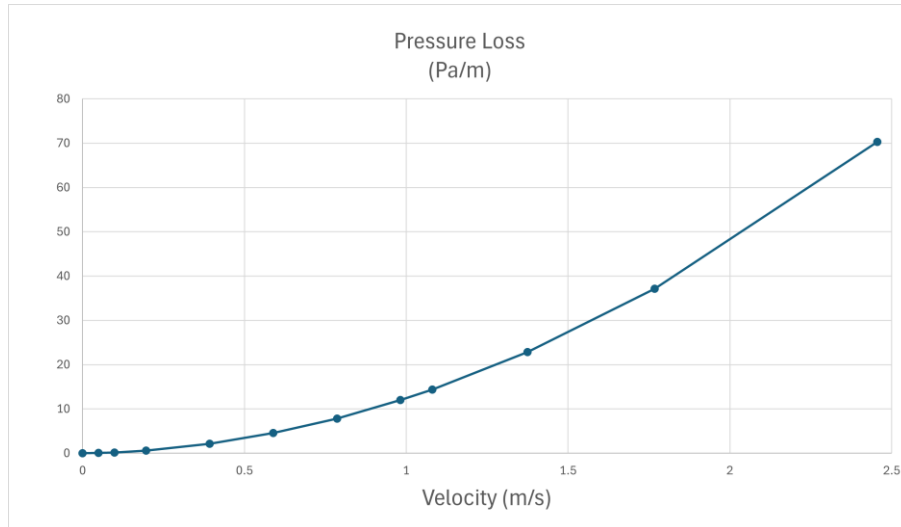


Figure 10 - Variation of pressure loss with flow velocity

This characteristic is important as will be shown later in the fifth chapter, where this strategy selected to identify leaks might be too dependent on the velocity of the fluid in the duct.

The Darcy-Weisbach friction factor is crucial in hydraulic engineering for calculating pressure drop, head loss, and flow distribution in piping systems. It influences the design, operation, and optimization of pipelines, pumps, valves, and other fluid-handling equipment. Accurate determination of the friction factor is essential for efficient and cost-effective system design and operation.

Localized losses in fluid mechanics, often referred to as minor losses, occur at specific points in a piping system such as bends, fittings, valves, and sudden changes in cross-sectional area.

The most common method to calculate localized losses is to use empirical formulas or coefficients that relate the loss to the geometry and flow conditions at the point of interest.

One of the widely used equations for calculating minor losses is the following:

$$h_f = K \frac{v^2}{2g} \quad 4.6$$

Where:

- h_f is the head loss due to localized losses
- K is the loss coefficient associated with the fitting or element

The loss coefficient K is determined experimentally for each type of fitting or element and depends on factors such as the geometry of the fitting, Reynolds number, and the roughness of the pipe surface. These coefficients are often provided in fluid mechanics textbooks or engineering handbooks for common fittings and components.

To calculate the total head loss in a piping system, we would sum up the losses due to friction along the length of the pipe (using the Darcy-Weisbach equation or other friction loss equations) and the losses due to fittings and other localized features using the appropriate loss coefficients.

Taking into account that this particular network has thousands of bends, fittings, valves, and sudden changes in cross-sectional area it was considered a tolerance value for these components. The tolerance for each section is available in Anex A. After calculating the frictional losses per unit of distance, we multiply this value by the tolerance to consider the localized losses.

4.4 Vale do Sousa Norte Subsystem

The Water supply system to be modeled in this dissertation is a subsystem of a network of the Porto district. It makes this distribution to its clients “*em baixa*”, a total of 22 municipalities, represented in Figure 11 below, under “*Municípios Clientes*”

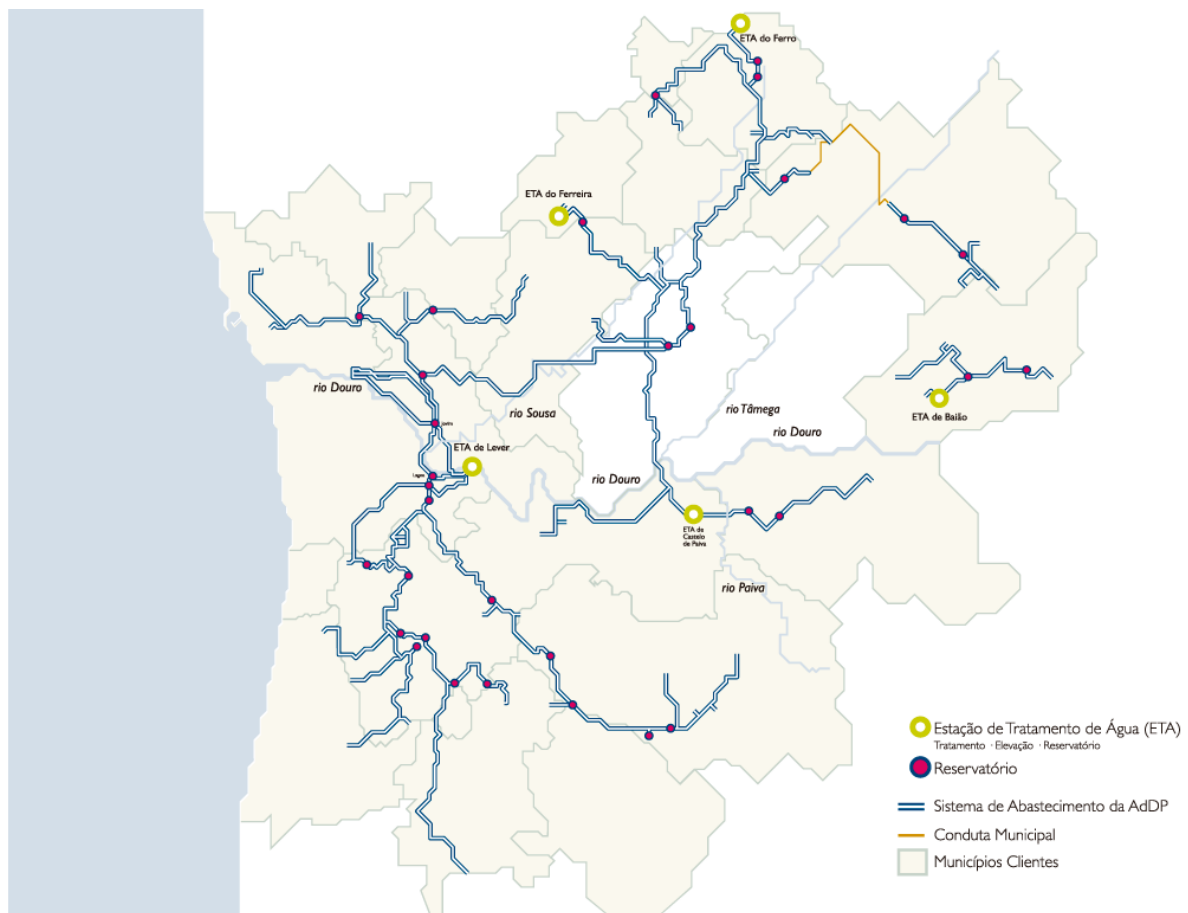


Figure 11 - Client Municipalities

The Vale do Sousa Norte subsystem to be modeled starts at a reservoir in Duas Igrejas, and distributes water gravitationally to other reservoirs owned by AdDP or owned by the municipalities. The other option is to deliver directly at “points of delivery” (*Pontos de Entrega*). From this point they will be referred to as simply PE.

There are some points that follow the same nomenclature as PE but are just internal points used by the company to acquire data. By that it means that there is no consumption for these. They are PE703, PE712, PE738, *Pombeiro* and *Vila Fria*.

PE710, PE716, PE725, PE745 are external delivery points (PE)

All the points and sections modeled for this dissertation can be visualized in Figure 12, Figure 13, Figure 14, and Figure 15.

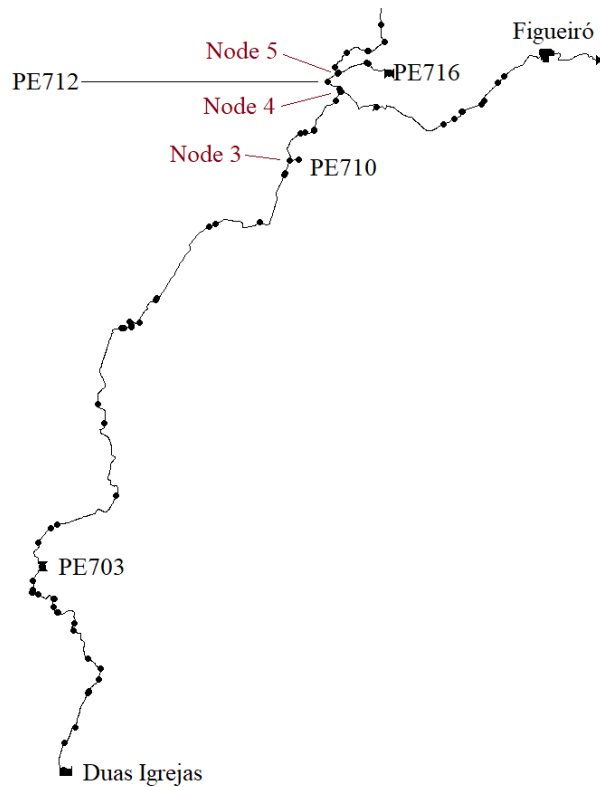


Figure 12 - Localization of nodes 1/4

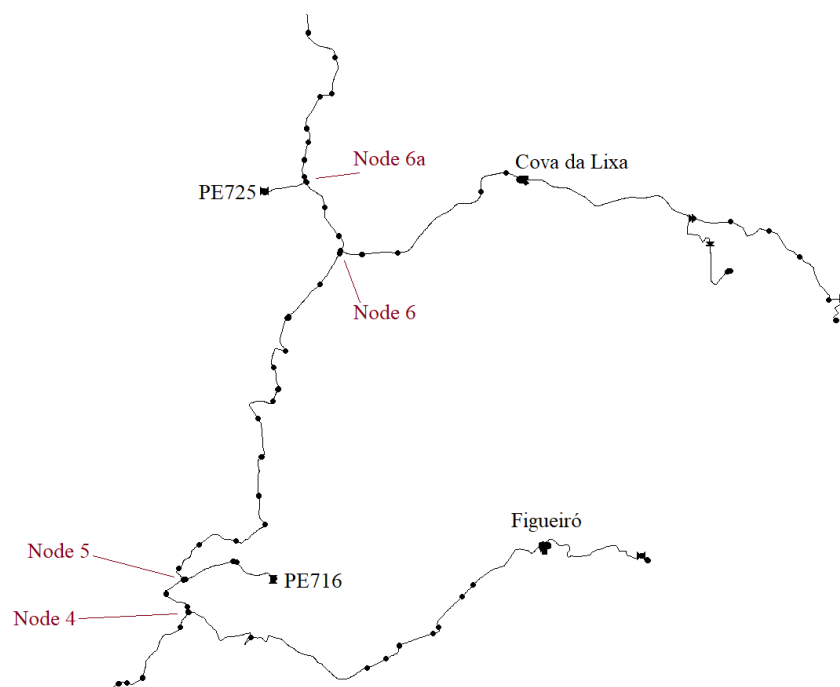


Figure 13 - Localization of nodes 2/4

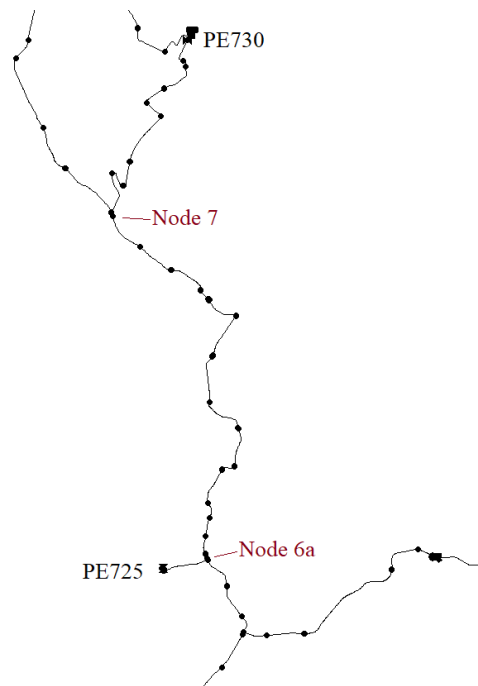


Figure 14 - Localization of nodes 3/4

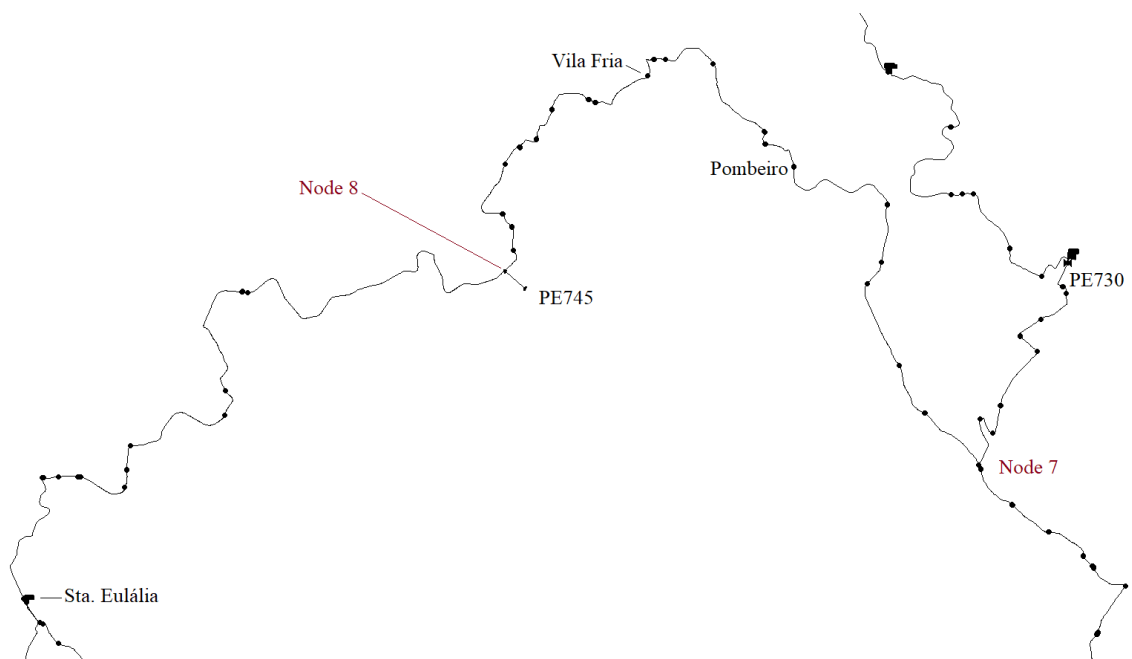


Figure 15 - Localization of nodes 4/4

In order to transform a real system to a mathematical model, it is sometimes necessary to discretize the problem.

Discretization, in the context of numerical methods and simulations, refers to the process of dividing a continuous problem or domain into discrete elements or segments. This is done to approximate the behavior of the continuous system through a set of discrete equations or values that can be solved using computational techniques.

It involves dividing the domain into smaller elements, such as cells, nodes, or elements, and then applying numerical methods to solve equations or perform calculations within each discrete segment.

The Vale do Sousa Norte subsystem can be discretized by a set of nodes and sections or branches. A branch or section is defined by a connection between two nodes.

In total, this subsystem contains a total of 20 nodes and 19 sections. Each node already has its own nomenclature, so it was chosen the following naming scheme for the branches as depicted in Figure 16.

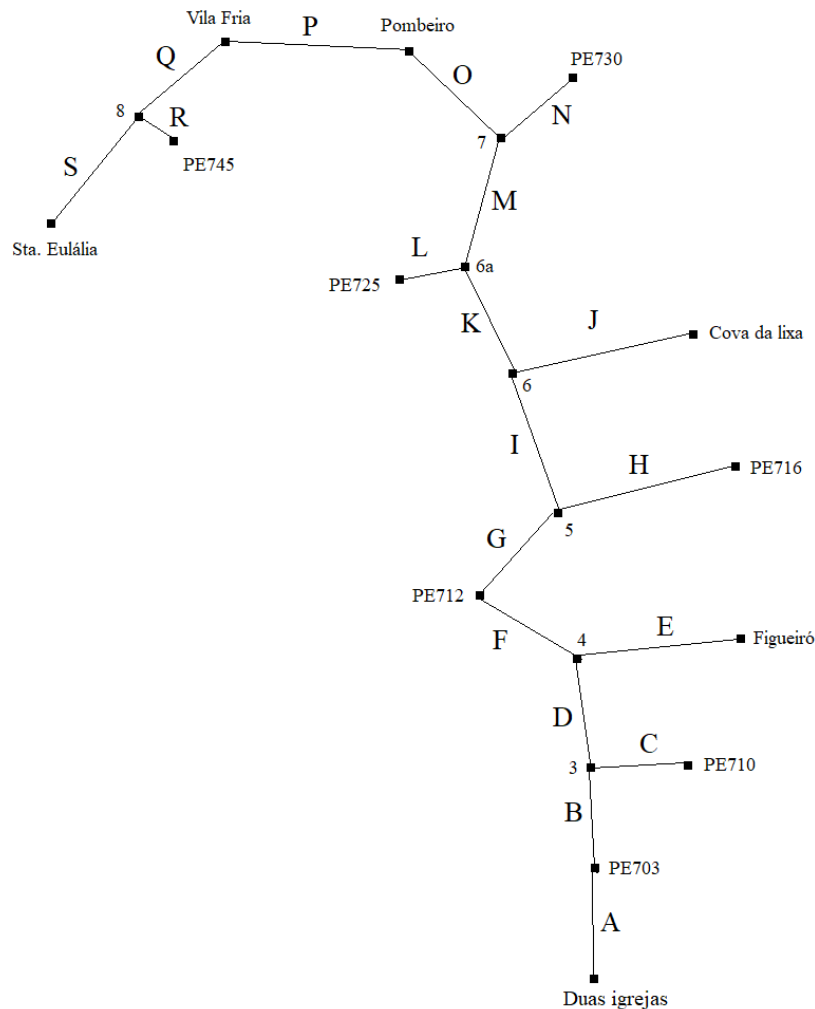


Figure 16 - Identification of Sections or Branch

- Branch A connects *Duas Igrejas* and PE703
- Branch B connects PE703 and Node 3
- Branch C connects Node 3 and PE710
- Branch D connects Node 3 and Node 4
- Branch E connects Node 4 and *Figueiró*
- Branch F connects Node 4 and PE712
- Branch G connects PE712 and Node 5
- Branch H connects Node 5 and PE716
- Branch I connects Node 5 and Node 6
- Branch J connects Node 6 and *Cova da Lixa*
- Branch K connects Node 6 and Node 6a
- Branch L connects Node 6a and PE725
- Branch M connects Node 6a and Node 7
- Branch N connects Node 7 and PE730

- Branch O connects Node 7 and *Pombeiro*
- Branch P connects *Pombeiro* and *Vila Fria*
- Branch Q connects *Vila Fria* and Node 8
- Branch R connects Node 8 and PE745
- Branch S connects Node 8 and *Sta. Eulália*

Numbered nodes 3 to 8 represent bifurcations, when there is a split in two branches.

Each node and section have its own separate attributes:

Table 2 - Nodes and Sections attributes

Nodes	Sections
Elevation	Duct Diameter
Localization	Total length
	Tolerance
	friction factor
	Flow
	Absolute roughness

As we can tell, we need all these variables and some constants (acceleration of gravity, water viscosity and density, etc.) to calculate the expected pressure at each node. Most of these variables like duct characteristics, elevation, etc. are available in the cadastral data of AdDP.

Considering that AdDP does not possess a meter in every single one of the 19 sections to achieve the flow data, there was a small challenge to estimate the flow for each section.

The sections that did not have the flow data were D, I, K, M, O, P and Q. Please notice in Figure 16 how the flow for O, P and Q will all be the same since these sections do not split in a bifurcation.

After collecting all the variables, we can make the calculation for a node in the system by knowing the first value where the water enters the system. That first point for this network is placed right outside the Duas Igrejas (D.I.) Reservoir. The pressure for this first point is simply dependent on the height of the reservoir, which thankfully is measured in real time.

$$P_{D.I.} = \rho g h_{Reservoir}$$

The calculation for the other nodes in the system are dependent on this pressure $P_{D.I.}$.

To achieve the pressure at a subsequent node, we apply the Bernoulli formula that considers the elevation and the velocity difference between the two points and then subtract the losses for the sections that connect the points.

As an example, if we want to know the pressure at node PE716, the calculation goes:

$$P_{PE716} = P_{D.I.} + \frac{1}{2}\rho(v_{D.I.}^2 - v_{PE716}^2) + \rho g(h_{D.I.} - h_{PE716}) - L_A - L_B - L_D - L_F - L_G - L_H$$

Some may make the mistake of using all the losses from the branches that go from the starting point to PE716 but the losses from section C and E are not used to achieve the pressure at PE716 because the flow to PE716 does not pass through those sections.

The same methodology applies to the other nodes.

5 Experimental Validation

After completing the theoretical model, it is always important to have available the physical media to conduct experimental tests, which the advisor and AdDP happily incentivized.

Several field tests were conducted in the *Vale do Sousa Norte* Sector for the following objectives:

- Validating the mathematical model.
- Determining the relationship between leak flow and pressure variation at the points before and after the leak.
- Determine which is the point of the network the pressure change will be more noticeable.
- Determine a threshold to signal an alert to the operational manager in the event of an anomaly.

In order to simulate a leak, a mains discharge was used like the one in Figure 17. Mains discharges are intended to allow the emptying of sections of pipelines and parts of distribution networks located between shut-off valves, in particular to carry out cleaning, disinfection or repair operations. They are located in the lowest points of the duct and in intermediate points with the same slope direction over relatively long lengths, considering the need to limit the emptying time of the conduits, and in extensive distribution networks in order to minimize the number of consumers affected by potential emptying operations.

The valve to discharge the water was opened slowly to not provoke a big impact on the flow inside the duct that we want to measure. After each turn of the valve, several minutes were let past and then opened a bit more to increase leak flow. These tests were always conducted with the support of the telemanagement data to calculate the sum of flows that enter and exit the system to estimate the leak flow.



Figure 17 - Mains discharge

5.1 1st Field test - *Cova da Lixa*

The first experiment was conducted in section J with a water flow entering the system close to zero. All the points of delivery for this system were shut down except for PE716 as this one wasn't allowed to stop.

The pressure sensor for the *Cova da Lixa* values is located at the suction side of the pumping station. The locations of the sensors and the location of the discharge must be well thought out.

The discharge was located immediately downstream of the pumping station of *Cova da Lixa*, which was probably not the best decision as will be discussed at the end of this subchapter after analyzing the pressure variation.

Starting to open the discharge slowly, over the course of 34 minutes, the system reached the final state depicted in Figure 18 reaching a maximum leak value of $30 \text{ m}^3 / \text{h}$.

PE730 is located after the bifurcation of node 7, not shown in Figure 18.

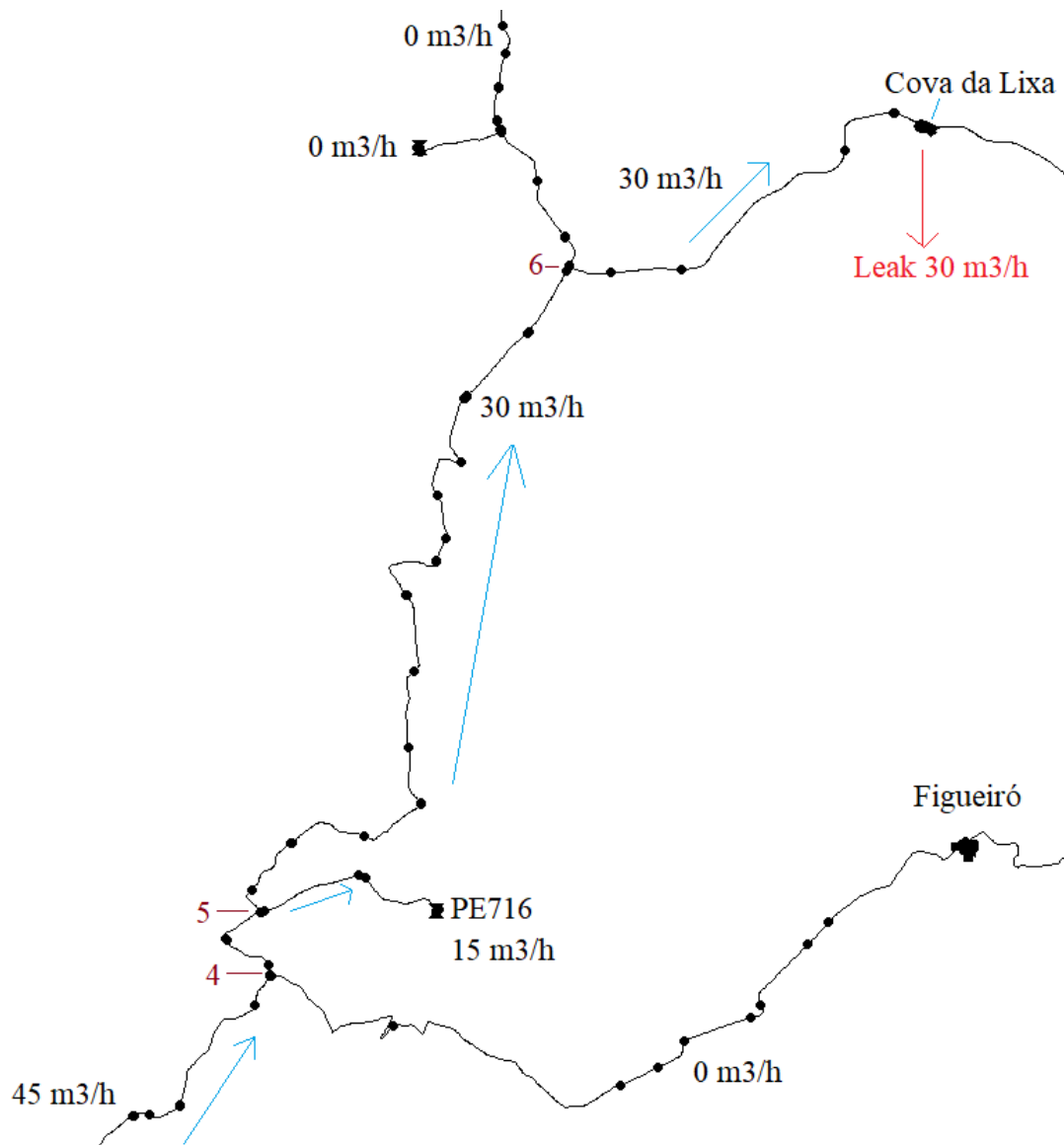


Figure 18 - 1st Field Test

After conducting the test, we can proceed to the telemanagement to acquire the data. The variation of pressure over the increase of leak flow in several points of the network is illustrated in Figure 19, Figure 20, Figure 21, and Figure 22.

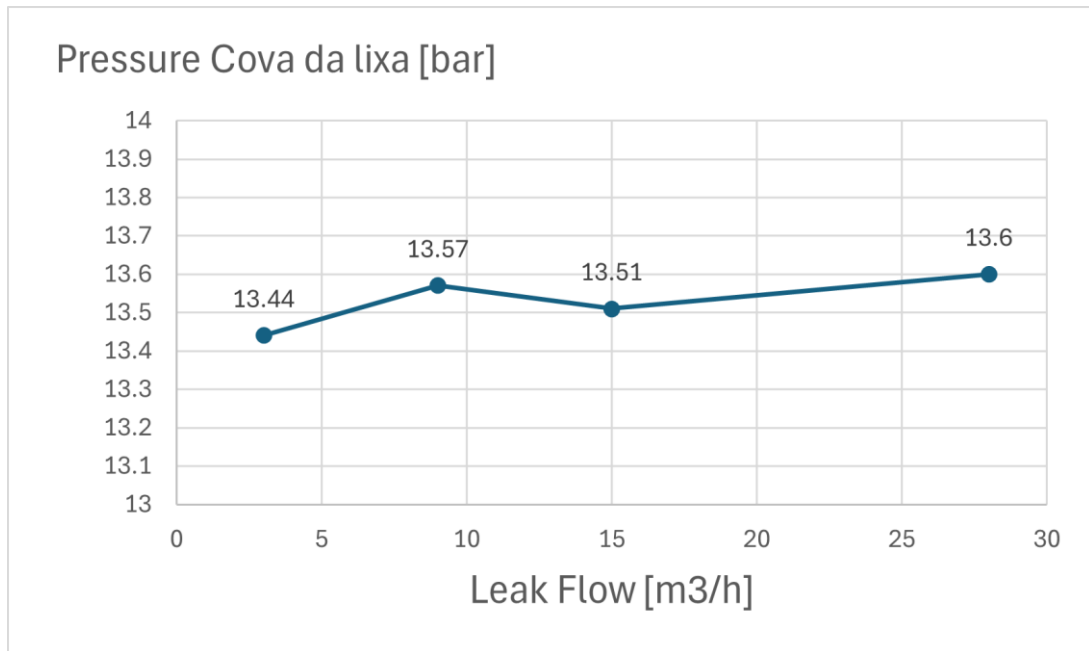


Figure 19 - 1st Field test Cova da lixa pressure

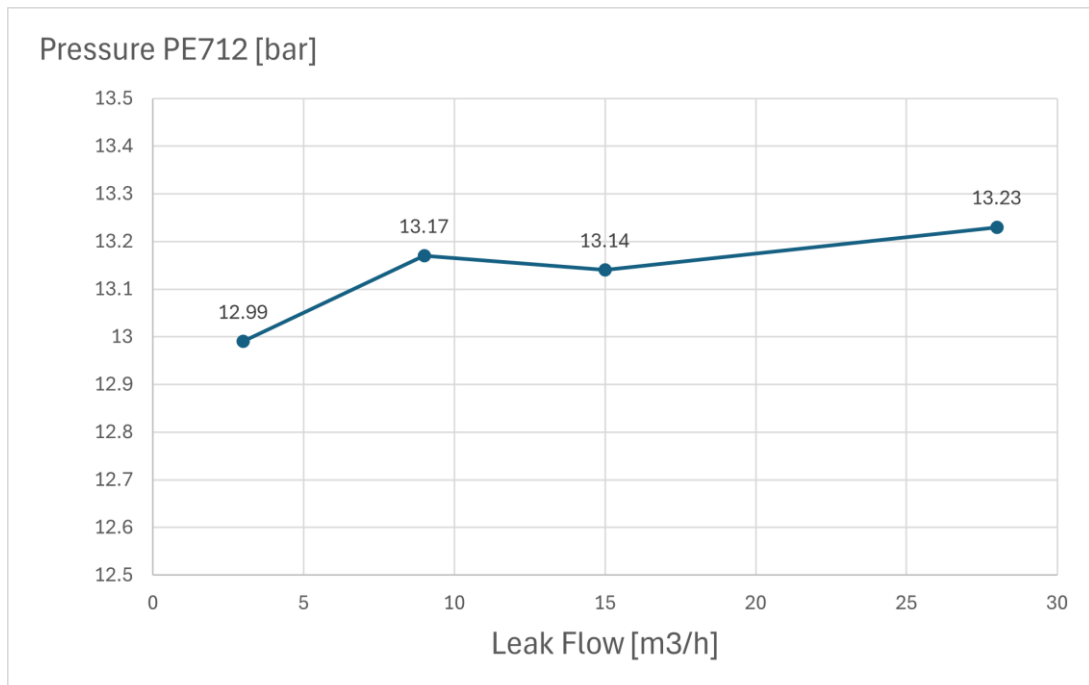


Figure 20 - 1st Field test PE712 pressure

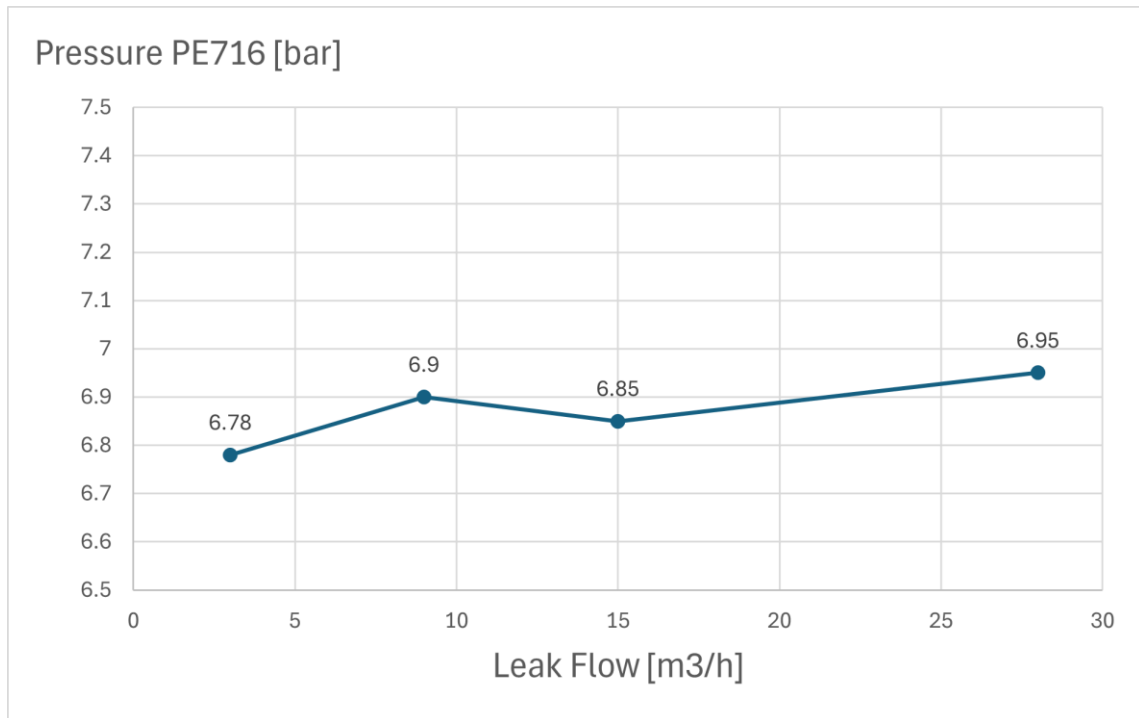


Figure 21 - 1st Field test PE716 pressure

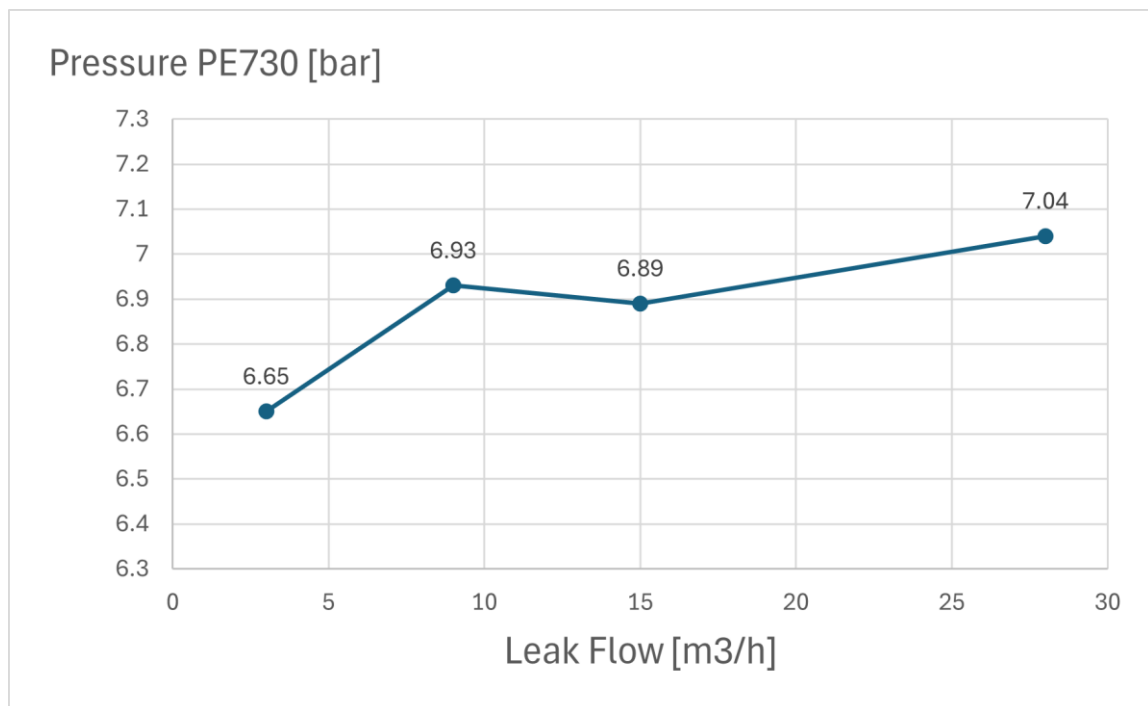


Figure 22 - 1st Field test PE730 pressure

Before conducting the test, the expectation from the author and the mentor was that, with the increase in flow and in velocity in the system, the energy losses would also grow. When the pumping station was turned off, the flow meter used for the model to calculate the losses in the section J would be at zero. But in reality, with the existence of a leak, the real flow at that section would not be null. The model would make the calculation for the pumping station turned

off (flow equal to zero) and give a higher pressure than the real one. If the difference became too significant, it would send an alert to the operational manager.

Some reasons as to why the pressure variation evolved this way might be:

- The reservoir at *Duas Igrejas* was filling during the experiment
- It's possible that the section downstream from the pumping station was emptying rather than upstream
- The existence of a retention valve between the pumping station and our discharge making the pressure readings invalid for the tests purpose

This test was therefore inconclusive.

5.2 2nd Field test - Cova da Lixa part 2

Dissatisfied with the results, it was decided to repeat the experiment but now on a discharge located 200 meters upstream of the *Cova da Lixa* pumping station. This time, the test was conducted while the Cova da Lixa pumping station was running. This way, any increase in flow on a branch will be more noticeable than if it was at zero.

The pressure sensor for the *Cova da Lixa* values is placed at the same location as before (suction side of the pumping station). The flow meter is located at the compression side.

Starting to open the discharge slowly, over the course of 30 minutes, the system reached the final state depicted in Figure 23, reaching a maximum leak value of $99 \text{ m}^3 / \text{h}$.

PE730 is located after the bifurcation of node 7, immediately before the *Felgueiras* Reservoir not shown in the figure.

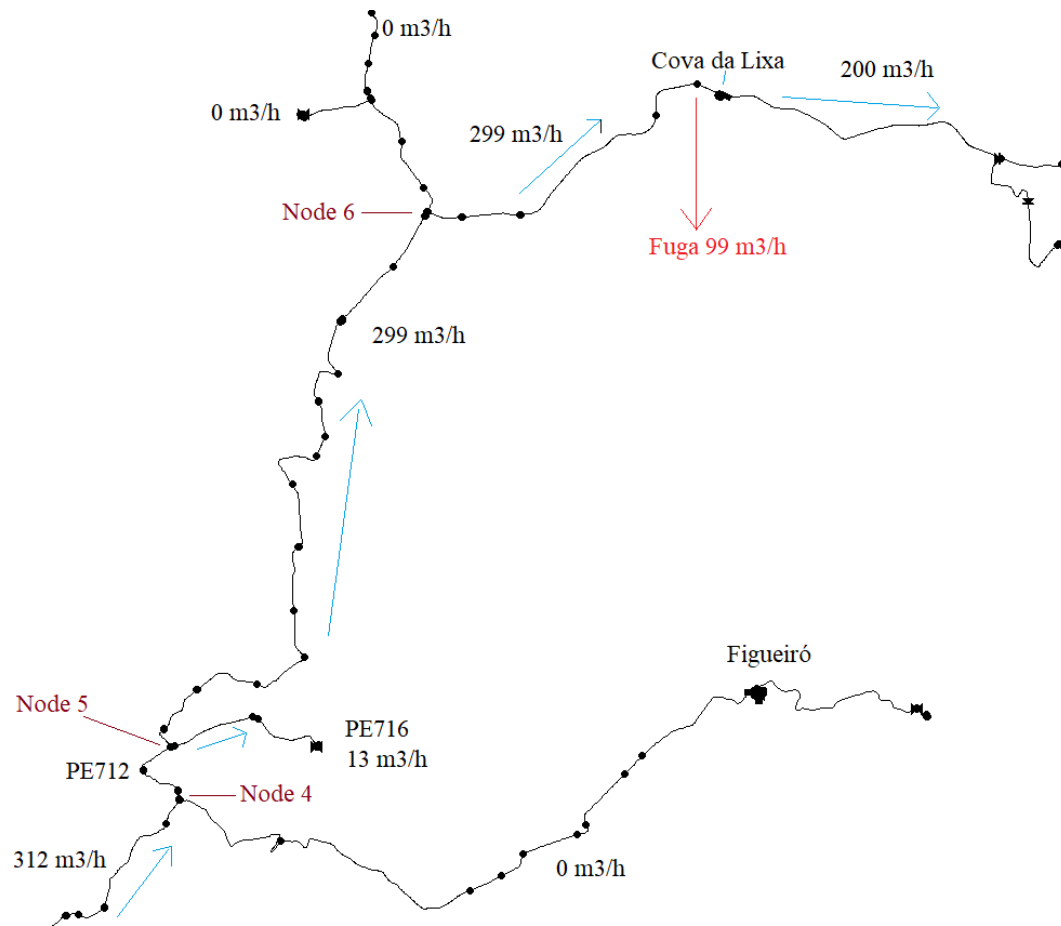


Figure 23 - 2nd Field Test

After conducting the test, we proceed to the telemanagement to acquire the data. The variation of pressure over the increase of leak flow in several points of the network is illustrated in Figure 24, Figure 25, Figure 26, Figure 27.

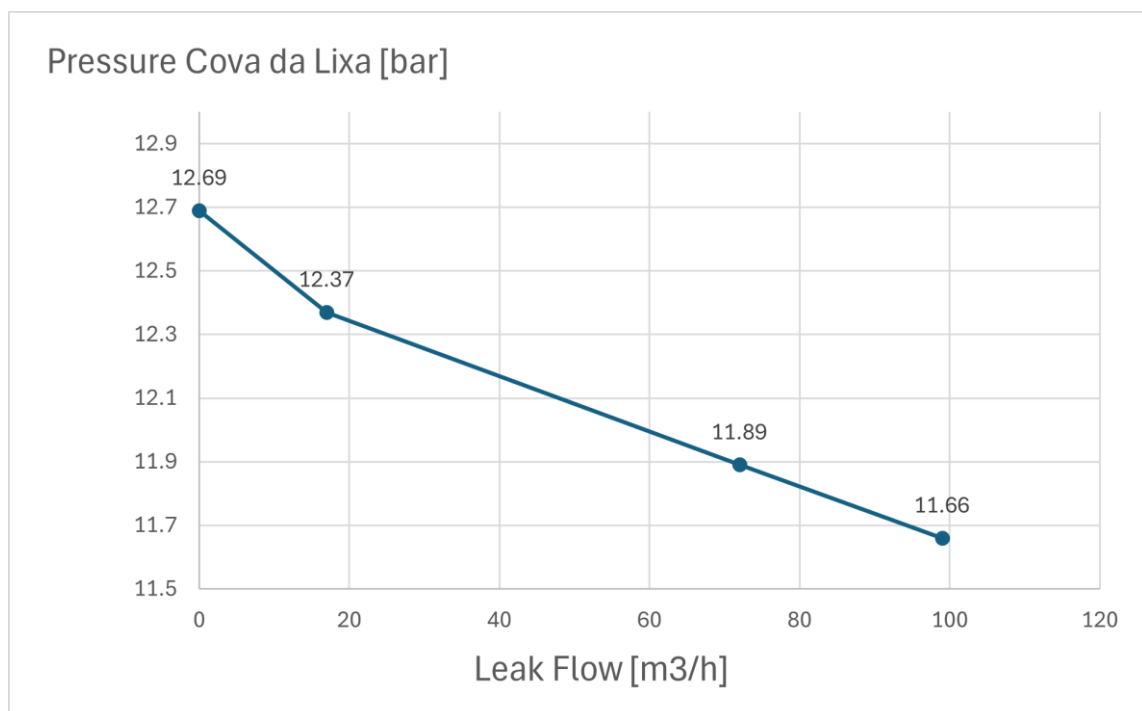


Figure 24 - 2nd Field test Cova da Lixa pressure

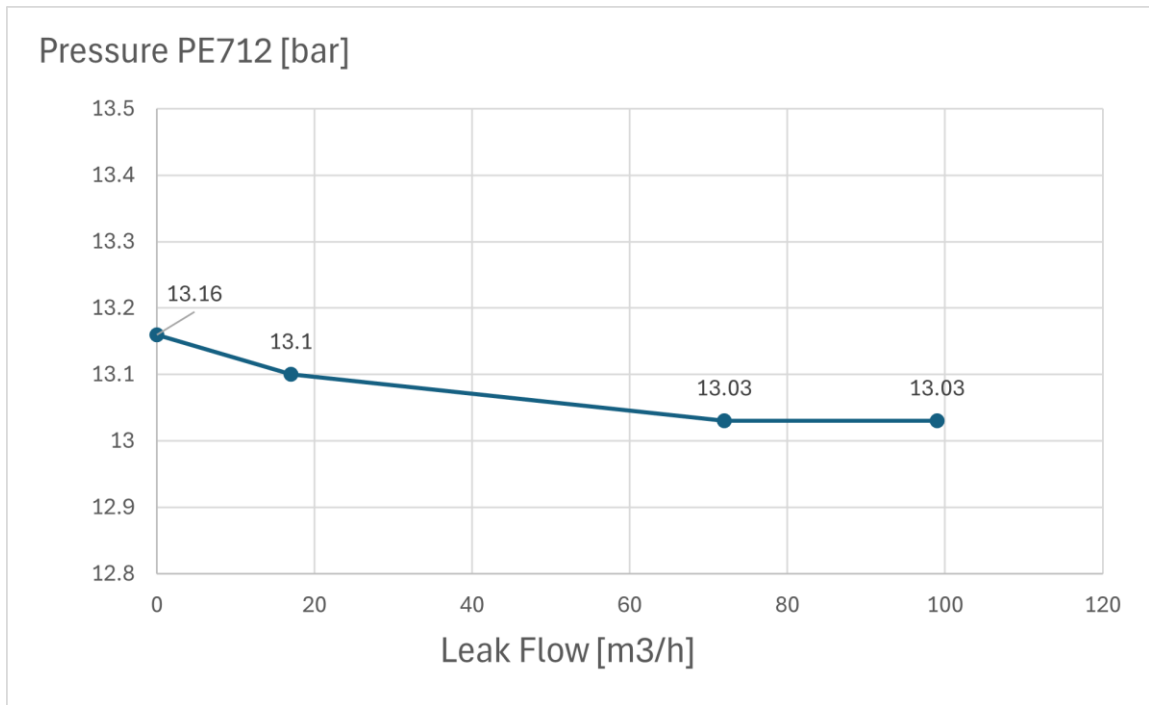


Figure 25 - 2nd Field test PE712 pressure

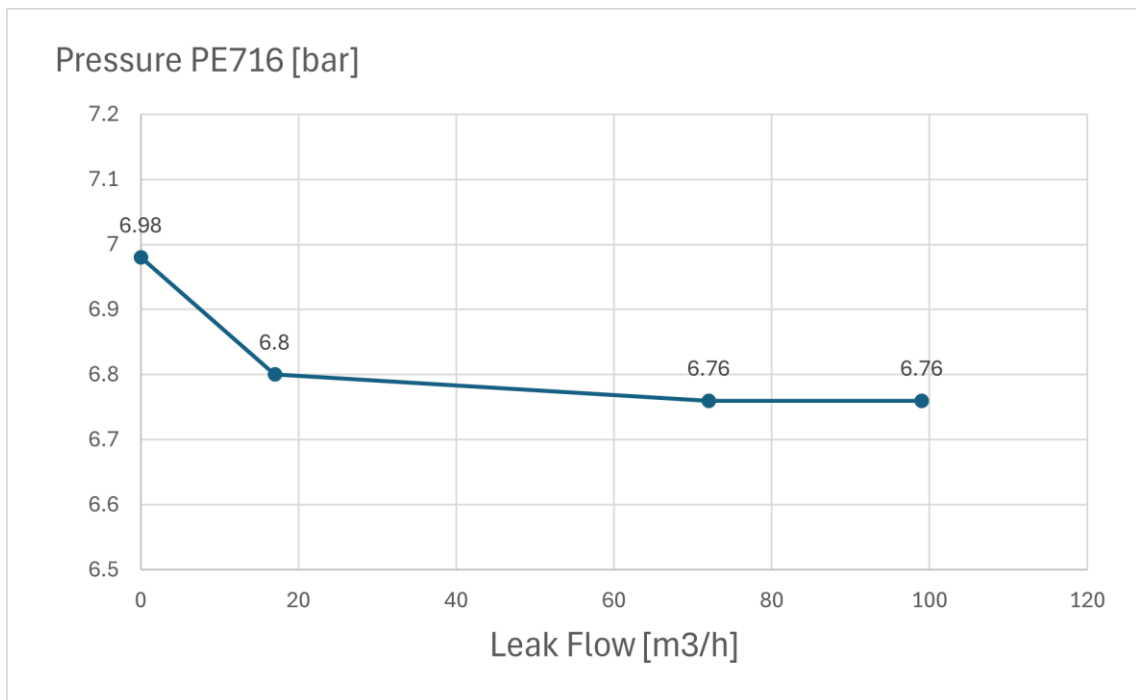


Figure 26 - 2nd Field test PE716 pressure

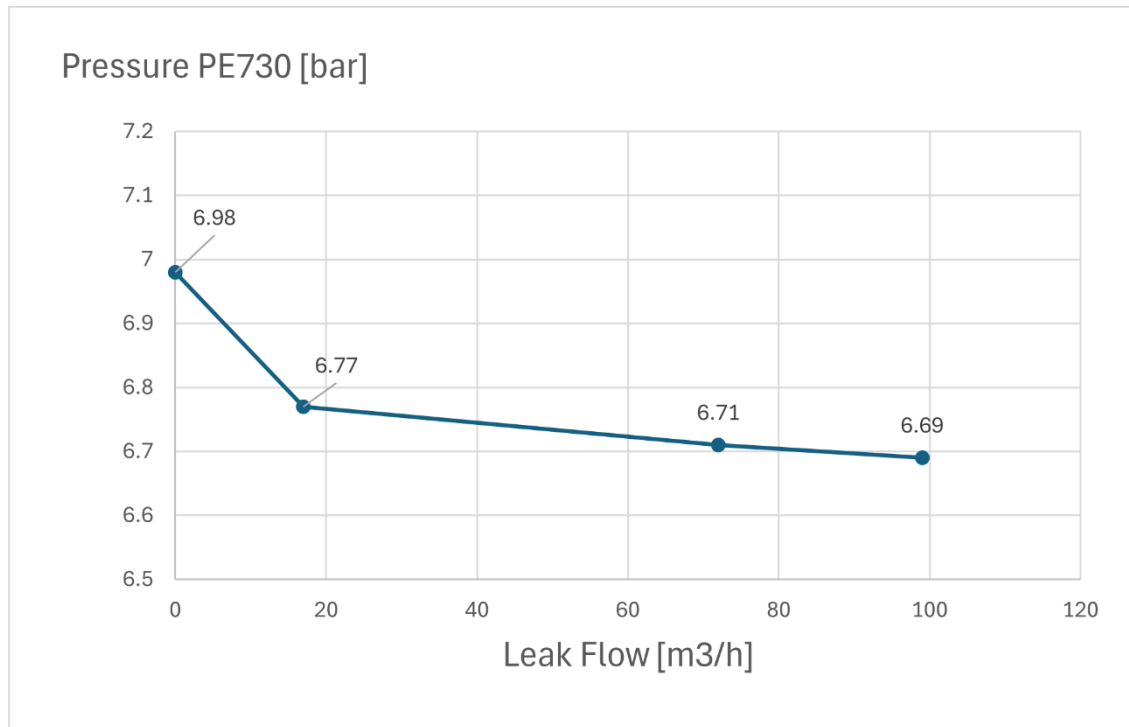


Figure 27 - 2nd Field test PE730 pressure

As the leak increases, the flow that leaves the *Duas Igrejas* Reservoir increases by the same amount since that is the only source of water that enters this network.

For point PE712, even though the pressure decreases, the value calculated by the model will also follow this pressure reduction. The pressure result from the model will also follow the same curve as the one depicted in Figure 25 because it uses the correct flow value that passes through it. This branch has a flow meter and a pressure sensor at the same location (PE712) illustrated in the figure. The model uses this flow meter to calculate the energy losses for this branch, so it gives a calculated result extremely similar to the real one.

After plugging all the inputs, the model outputs an estimated pressure of 12.95 bar for PE712 while the sensor outputs 13.03 bar, a small difference of 0.08 bar which is small and likely inside the margin of error of the pressure sensors.

Following the same logic, and with a flow of around $200 \text{ m}^3 / \text{h}$ getting pumped in *Cova da Lixa*, we get a calculated pressure of 12.36 bar while the sensor was measuring 11.66 bar. This is a much bigger and significant difference of 0.7 bar, an order of magnitude higher than the previous value, thus giving a sign of validating the model. It calculated the pressure at *Cova da Lixa* assuming that the flow passing through the section “I” was just $200 \text{ m}^3 / \text{h}$ when in reality it was $299 \text{ m}^3 / \text{h}$.

The same reasoning used for PE712 applies to PE716. Even when the flow that passes through branch “H” remains constant at $13 \text{ m}^3 / \text{h}$, the increase in flow at sections A, B, D, F and G is also used by the model. So the calculated result from the model will follow the same curve as the real one. Since there isn’t a significant difference, an alert is not sent to the operational manager.

The pressure drop at *Cova da Lixa* was approximately 0.1 bar per each $10 \text{ m}^3 / \text{h}$ of leak flow, which is quite significant. These values are important to measure to gain some awareness of what are the orders of magnitude associated with large water supply systems.

One interesting result that wasn’t expected was the pressure drop at points in the system that supposedly have zero flow at the time of the test like the one for PE730.

5.3 3rd Field test - Vizela

The third experiment was conducted in a different branch from the previous two. It took place in *Vizela*, in the branch that connects node 7 to node 8. Node 8 is a bifurcation that leads to PE745 *Penacova* and the other duct continues until it reaches the *Sta. Eulália* pumping station.

This discharge in *Vizela* is located 1.5 kilometers upstream of node 8, *Vila Fria* 1.8 km and *Pombeiro* 2.1 kilometers as shown in Figure 28.

The data that was chosen for this trial were the pressure sensors for *Pombeiro*, *Vila Fria*, PE745 and *Sta. Eulália*. The sensor for PE 745 is located a few meters after Node 8, placed on the duct that goes towards *Sta. Eulália*. The *Sta. Eulália* sensor is located at the suction side of the *Sta. Eulália* pumping station.

The sensors for *Pombeiro* and *Vila Fria* can be seen in Figure 28.

Starting to open the discharge slowly, over the course of 20 minutes, the system reached the final state depicted in Figure 28 reaching a maximum leak value of $48 \text{ m}^3 / \text{h}$.

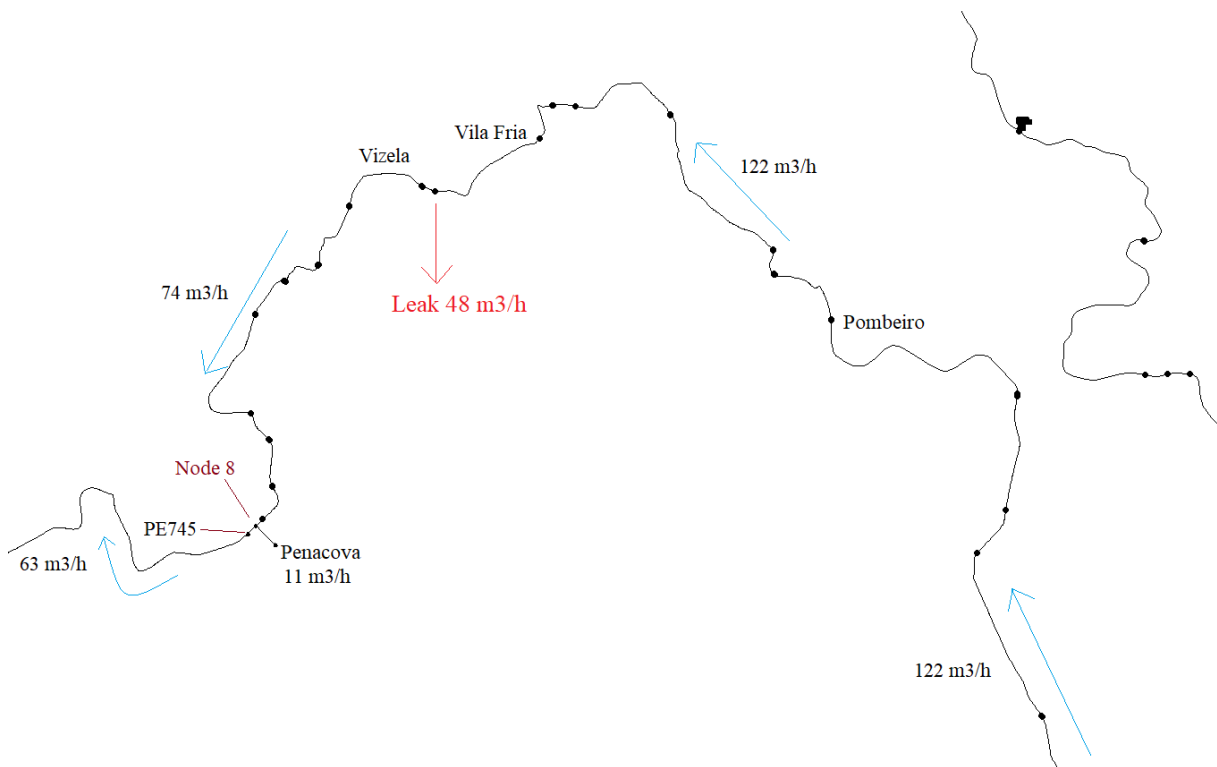


Figure 28 - 3rd Field Test

The final results can be seen in Figure 29, Figure 30, Figure 31, and Figure 32.

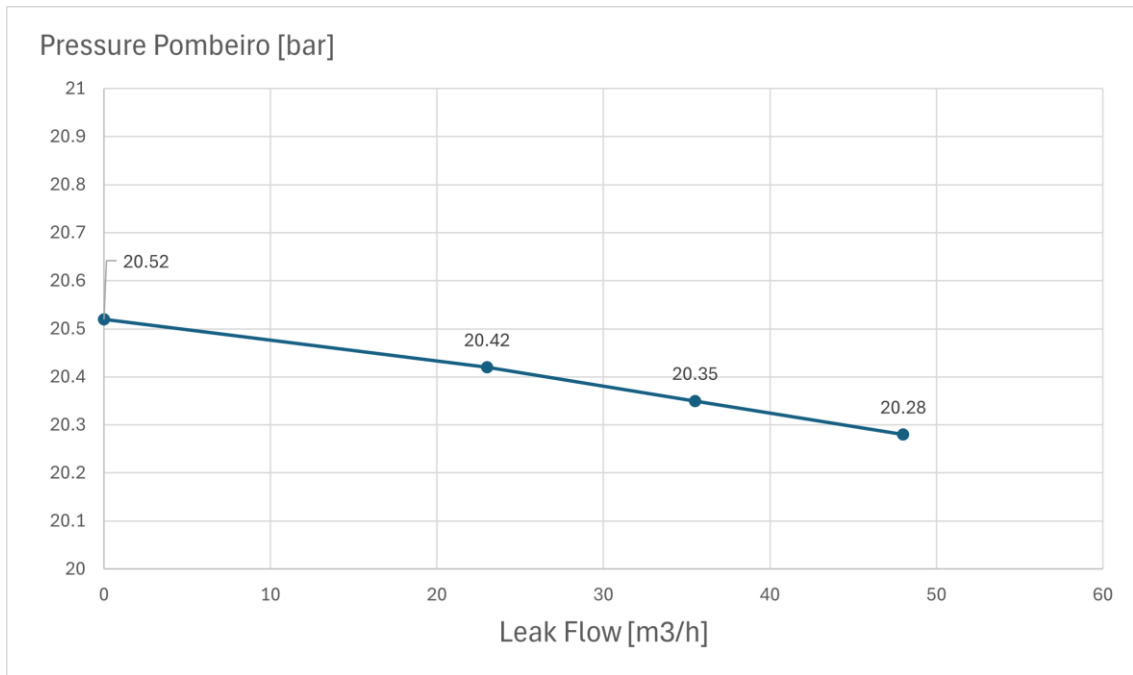


Figure 29 - 3rd Field Test Pombeiro Pressure

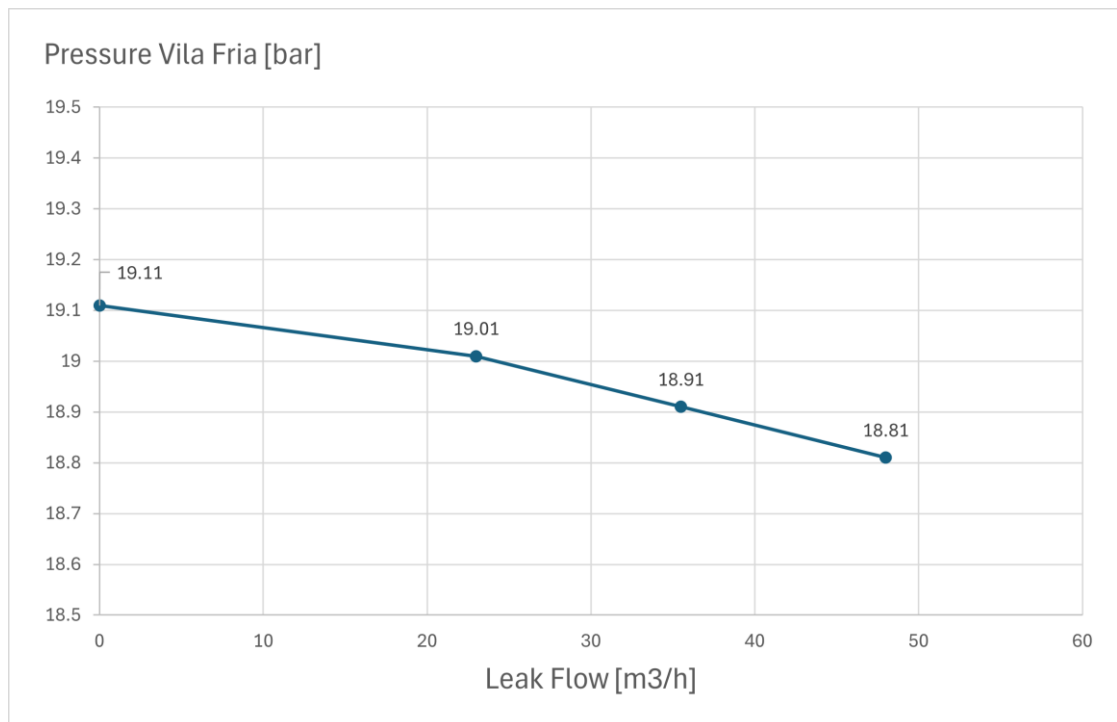


Figure 30 - 3rd Field Test Vila Fria Pressure

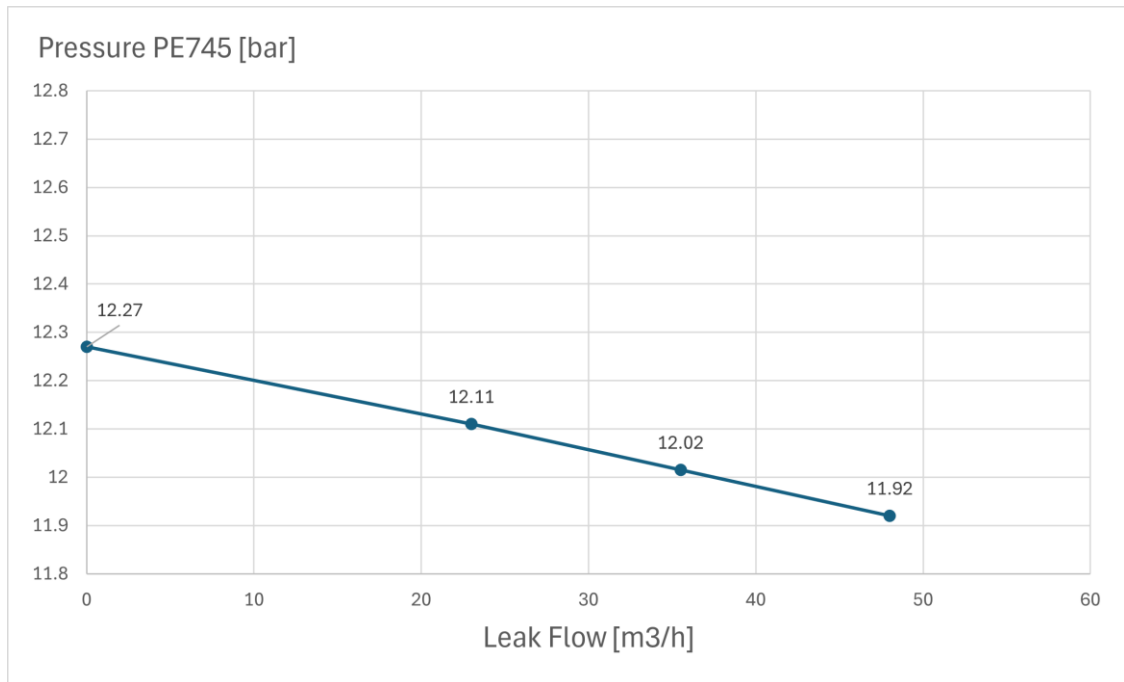


Figure 31 - 3rd Field Test PE745 Pressure

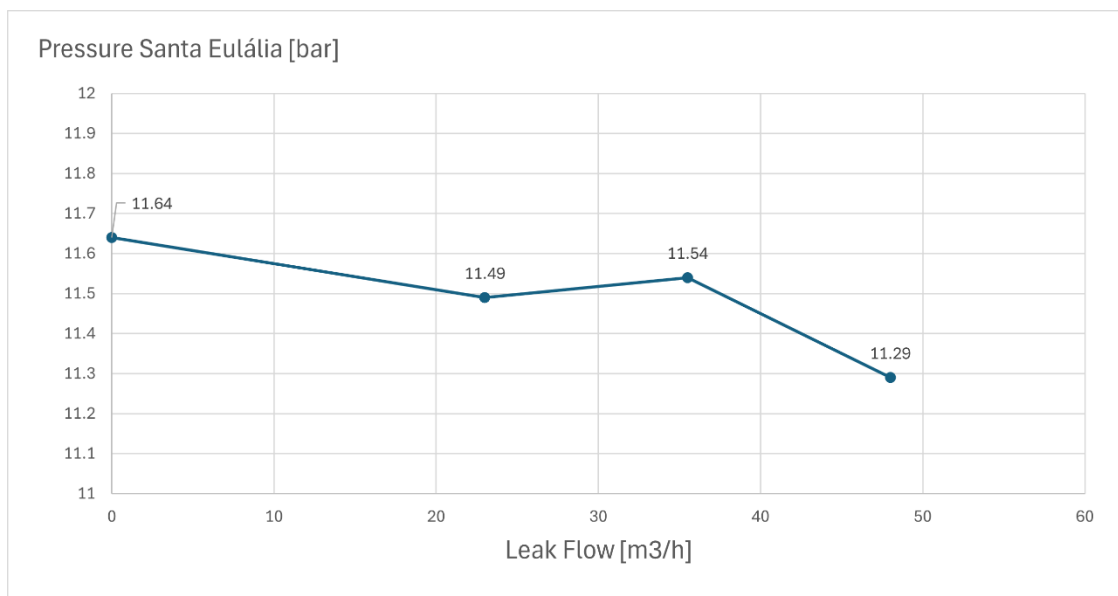


Figure 32 - 3rd Field Test Sta. Eulália Pressure

The absolute value for pressure reduction caused by the leak can be seen below:

Table 3 - Pressure drop for 3rd test

Sensor values	Pombeiro	Vila fria	PE745	Sta. Eulália
Pressure Drop (bar)	0.24	0.3	0.35	0.35

After inputting all the data, we can compare the real values (for the Leak flow = $48 \text{ m}^3 / \text{h}$) with the ones from the model and analyze the difference:

Table 4 - Model and sensor pressure values for 3rd test

	Value from model [bar]	Value from sensor [bar]	Difference between model and sensor [bar]
Pombeiro	20.32	20.28	0.04
Vila Fria	18.89	18.81	0.08
PE745	11.9	11.92	-0.02
Sta. Eulália	11.14	11.29	-0.15

Regarding Pombeiro and Vila Fria, the situation is a bit different. As it stands, there isn't any flow meter installed in section (Node 7 and 8). In order to calculate this value, the telemetry does the simple calculation:

$$\text{Flow "O"} = \text{Flow "M"} - \text{Flow "N"}$$

This means the model is using the real flow that passes in that section so the values will go in line with reality.

If we want to use this model to identify that a leak is occurring before Pombeiro, then that means I need to know the true flow that arrives in Pombeiro.

These experiments were very important to understand the true limitations of this methodology. Using Figure 33, in a flow that travels from point 1 to point 2, with this model, it can only detect a leak in the branch if it measures the energy losses in the branch by only using the flow that passes through point 2. In this model, if we calculate the pressure at point 2 using the flow from point one, then the model will calculate correctly the energy losses that go from point 1 until the leak. After that it is overestimating the flow (and energy losses) that proceed from the leak to point 2. In this scenario, the model would actually give a lower value than the real one at point 2.

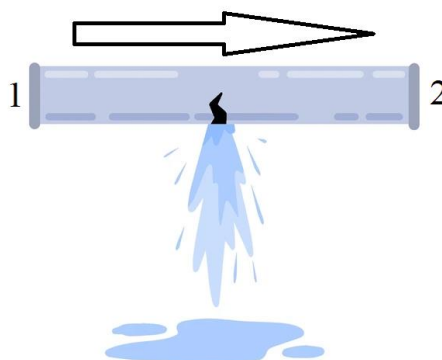


Figure 33 - Simple depiction of a leak

This exact situation can be confirmed in the values for PE745 and Sta. Eulália. In the latter, the model used the value of $122 \text{ m}^3 / \text{h}$ for the section that goes from the leak to PE745, even though after the leak there was only $74 \text{ m}^3 / \text{h}$. The model overestimates the pressure losses and gives a value lower than the real one. The difference was very small, so it is necessary to be careful to draw conclusions, as there is a margin of error associated with every experiment.

This peculiarity is hard to avoid if a water management entity does not have access or the capital to install a flow meter immediately upstream of each node. This would be even harder for a management entity “*em baixa*” due to the significantly greater number of nodes and branches.

6 Conclusions and future work

Water supply systems are essential for economic and social development. Each one with its own complexities. The water distribution networks are the buried component of the system that accompanies the development of humanity with the aim of enabling the household distribution of water. All distribution networks have water losses and leaks, a substantial component of non-revenue water.

Real losses occur randomly at any location, with or without apparent justification. They represent inadequate management from a financial, economic, and environmental perspective, resulting in the waste of numerous material and natural resources, energy, and associated high costs. Low pressure entities face harder challenges than their high pressure counterparts since their distribution networks contain many more nodes, links, connections, meters, sensors, and they have to respond to hundreds of thousands of clients while, for example, AdDP only answers for 22.

To secure sustainability, management entities must enhance their technical expertise and financial independence. One avenue is to lower water service expenses by minimizing the overall volume of real losses. However, cost reduction through loss volume reduction is effective only up to the point of reaching the economic level of losses. Any further reduction below this level incurs higher costs than those saved from water losses. Among the several approaches to reach this threshold, locating leaks emerges as a conclusive solution that can prematurely avoid dangerous events that pose risk to life and can become a major factor in lowering energy consumption. Ribeiro (2016)

The dissemination of calibrated mathematical models to simulate the hydraulic behavior of water distribution networks is of great importance. Valid responses can only be extracted from these models when they accurately represent reality, particularly with the correct description of network characteristics, topology, and all details in boundary conditions. Ribeiro (2016)

Additionally, monitoring and control systems have been gaining prominence and will soon become essential sources of information for the management and daily operation of the network and the management entity. A mathematical model is proposed to assist in the approximate location of leaks in water distribution networks, drawing from the intersection of these realities by using real time operational data.

Starting by the initial conditions of the proposed challenge (only using data from sensors and meters through the network), the strategy chosen was to model the network using fluid mechanics equations that describe the relationship between all the different attributes that define a system comprised of fluids in motion. With this, it predicts what is the expected pressure for each node in the duct network assuming that there are no leaks. After estimating those values, it compares them with the existing pressure sensors. In the event of a leak, the extra frictional losses would not be accounted for by the model and would calculate a value higher than reality. After conducting several experimental tests, the conclusion was reached that this methodology only works when using the real flow that reaches a node to calculate its pressure. For this to occur, it is necessary to have a meter very close to the point where the pressure is being measured by a sensor. Since we can only compare values with points that have a pressure sensor, this means that each one of its locations is a node.

There are several sections of the network that do not have a flow meter associated with, so some values had to be calculated to complete the calculations. This is one of the limitations of this model.

More limitations of this methodology are described below:

- The solution given by this mathematical method does not provide the exact coordinates of the leak, it only indicates the branch with the anomaly. After this, the section requires further analysis with precise location techniques, avoiding the necessity of tracking the leak in areas that would be futile to search.

- The bigger the section between two nodes, the harder will be to precisely locate the leak.

- Due to the nature of the fluid mechanics equations used, the model is very dependent on the value of the frictional losses. This means that the model does not work very well when the flows in the system are small.

- An empirical value of pressure difference between the model and the sensor to signal an alert might not be the best approach. Knowing that the linear losses evolve exponentially with velocity, a change of flow when the system is distributing a lot to its clients wont be the same as when the clients have low consumption (at night for example).

- The model might be better used in distribution systems with higher velocity.

- This model only works with one direction of flow.

- To calibrate the tolerances to apply to each section, the data from telemanagement was used. This was done assuming that the system has no previous leaks, which might be an incorrect assumption.

- The experimental tests are only valid assuming that there were no leaks at the time of their occurrence.

The process of capture, treatment, pumping and distribution of water is very energy intensive. For the case of Vale do Sousa Norte, for the water to reach its farthest locations for delivery to the municipalities, sometimes have to go through several reservoirs, pumping stations and recoloration stations. Every step of the way consuming resources to beat changing topography a lot at times for a client with many deficiencies and high water loss rates. For the outermost regions, the specific energy consumption reaches values around $2.4 \text{ kwh}/\text{m}^3$. Considering the average daily consumption of around 40000 m^3 , this means a total of $35.04 \text{ gwh}/\text{year}$. A small amount of 1% of water loss in this system represents a consumption of 350 mwh . Using an average for emissions value of $225 \text{ gCO}_2/\text{kwh}$, this would correspond to a total of 80 tons of CO_2 released.

6.1 Future Work

Considering the previous conclusions, several things could be changed to improve the model and certain aspects could have been handled differently. Provided below is a list for future work:

- Conduct more tests at the same locations but with different flows.

- Perform a study with the goal of finding the appropriate difference value between model and sensor that would signify a leak and alert the operational manager. This might be a certain percentage of the pressure value or even establishing a relationship that lowers this threshold value as the flow in the section increases (a duct with a higher flow will be easier to detect a leak).

- Installing more flow meters at the point of pressure measure.

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Anex A - Nodes and Section attributes

Node and Section attributes:

Section	Length	Diameter	Tolerance
	[m]	[m]	%
A	4955	0.6	15
B	10951	0.6	5
C	130	0.15	5
D	1721	0.6	15
E	4797	0.45	0
F	311	0.6	0
G	236	0.6	15
H	1049	0.2	15
I	4769	0.5	15
J	2237	0.25	-15
K	842	0.45	15
L	470	0.2	15
M	4335	0.45	15
N	2561	0.35	15
O	3562	0.3	0
P	1993	0.3	0
Q	2741	0.3	0
R	5	0.3	0
S	7555	0.25	-10

Node	Elevation
	[m]
Duas igrejas	419.0
PE703	347.3
3	283.6
PE710	291.6
4	271.2
Figueiró	350.4
PE712	288.0
5	291.5
PE716	352.0
6	12.5
Cova da Lixa	283.9
6a	301.4
PE725	340.7
7	301.7
PE730	346.8
Pombeiro	202.1
Vila Fria	215.2
8	215.2
PE745	284.3
Sta. Eulália	290.3

Constants:

Dinamic viscosity of water	0.0010518	$Pa \cdot s$
Absolute roughness	0.0001	m
Acceleration of gravity	9.81	m / s^2
Water density	997	kg / m^3