

Master Thesis  
TVVR 26/5006

# Hydraulic Modelling for Performance Assessment and Operational Optimization of a Drinking Water Supply Distribution Network

A case study in Kirke Eskilstrup,  
Denmark

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Box 118  
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Water Resources Engineering  
TVVR-26/5006  
ISSN 1101-9824

Lund 2026  
[www.tvrl.lth.se](http://www.tvrl.lth.se)

Master Thesis  
Division of Water Resources Engineering  
Department of Building & Environmental Technology  
Lund University

English title: Hydraulic Modelling for Performance Assessment  
and Operational Optimization of a Drinking Water  
Supply Distribution Network, A case study in Kirke  
Eskilstrup, Denmark  
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Examiner: Kenneth M. Persson  
Language: English  
Year: 2026  
Keywords: Drinking water distribution system, optimization,  
hydraulic modelling, DWDS



# Acknowledgements

This thesis project was carried out in collaboration with Ramboll Denmark. I want to express my gratitude to my co-supervisors from Ramboll, Wei Han and Carl Stagne, for their technical guidance, practical insights, and support throughout the development of this project.

I would also like to thank my supervisor from Lund University, Magnus Larson, co-supervisor Erik Nilsson, and examiner Kenneth M Persson, for their valuable feedback and support during the thesis project. Their guidance helped improve the direction, structure, and technical quality of this work.

I am deeply thankful to my partner, family, and friends for their constant love, support, and encouragement. They helped me stay motivated throughout the challenges of this thesis and my studies.

I would also like to thank DHI for granting access to the MIKE+ student license and guidance materials. This made the hydraulic modelling in this thesis possible.

This thesis project was completed during my scholarship period at Lund University, funded by the Swedish Institute. I am sincerely grateful for the opportunity that made it possible to pursue my master's studies and complete this project.



## Abstract

Even minor disruptions in drinking water distribution systems can affect daily activities, public health, and the reliability of essential water services. This study evaluates the hydraulic performance and operational efficiency of the Kirke Eskilstrup drinking water distribution network in Denmark using hydraulic modelling in MIKE+. Furthermore, a stakeholder value analysis was included to identify how the modelling results can support practical decision-making and long-term system planning.

This study integrates utility records, GIS data, consumer demand data, pump information, and field pressure measurements to develop, calibrate, and validate a hydraulic model of the current system. The calibrated model was used to evaluate current operating conditions and two scenarios: leakage under normal demand conditions and leakage under high-demand conditions. The results show that the system can maintain hydraulic service under the simulated conditions, although several high-pressure nodes were identified as potential leakage-sensitive points. Pump\_1 was found to be sufficient as the main supply pump, while the booster pumps showed lower efficiency despite variations in energy consumption.

The findings indicate that the main optimization opportunities are related to leakage monitoring in high-pressure areas, review of booster pump operation, and further investigation of tank-based pump scheduling. Although the simulated cost increase was small, leakage represents a continuous and avoidable operational cost, while inefficient booster operation may reduce long-term system efficiency. The results, therefore, provide practical decision support for Kirke Eskilstrup waterworks by identifying priority areas for improving pressure management, pump efficiency, and future operational planning.



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# 1. Introduction

## 1.1. Background

The quality of life, health, and sanitation are all significantly impacted by the drinking water distribution network. Even minor interruptions in the operation of these systems can have a negative impact on the quality of human life (Souza et al., 2025). This is crucial because a reliable water supply is necessary for everyday human activities. Consequently, failures, disruptions, or changes from the standard operating state can have significant negative effects. This implies that a reliable, efficient, and well-maintained drinking water distribution system is an important part of an urban area (Teichmann et al., 2020).

It is a fact that water distribution systems are complex due to the need to balance hydraulic performance, energy use, and infrastructure constraints. Pumps must be operated to meet water demands across the network, but this directly influences system pressure. When pressure becomes insufficient, it can prevent water from reaching higher elevation areas; however, too high pressure can result in pipe leakage, pipe deterioration, and unnecessary energy cost. In addition to pumps and pipes, water distribution systems include components such as valves, tanks, reservoirs, and control devices, all of which interact to complicate system operation. Therefore, optimizing the system of even a small-scale water distribution network remains a challenging problem (Vieira et al., 2020; Teichmann et al., 2020).

Urban water distribution networks contribute to roughly 2.6% of overall electricity usage in the EU, mainly from the pumping of underground water. Minimizing water losses in the system has a chance to conserve considerable amounts of energy and help with greenhouse gas reduction efforts (Díaz-Cano et al., 2025). Therefore, the EU Directive 2020/2184–Recast Drinking Water Directive–sets a 15% threshold for losses in water distribution networks. It is an important policy within the European Union that focuses on improving the management of drinking water supply and establishes a formal approach for setting water efficiency targets (Díaz-Cano et al., 2025).

Hydraulic assessment and optimization using hydraulic models are useful tools to better understand system behaviour, identify operational inefficiencies, and

support decision-making for more reliable and sustainable water distribution management. Therefore, optimizing the system of Kirke Eskilstrup presents a significant opportunity for the water utility to reduce energy consumption while contributing to more sustainable system performance.

This degree project is a collaboration among Lund University, Ramboll, and Kirke Eskilstrup Vandværk, with the water distribution network of Kirke Eskilstrup as the main study area. All information needed to carry out the project was provided by the water utility company and Ramboll, as well as parts of the supervision.

## **1.2. General and Specific Objectives**

The general aim of this thesis project is to evaluate the current performance and operational behaviour of Kirke Eskilstrup water distribution network under normal and high-demand operating conditions and to identify opportunities for improving operational efficiency.

The specific objectives of this study are to:

- Assess the hydraulic performance of the system and identify possible limitations and bottlenecks in the distribution,
- Evaluate and identify potential opportunities for improving pump operational performance and efficiency,
- Provide technical results and suggestions to the water utility company to support decision-making and strategic planning for the future development and management of the water distribution network for the coming five to ten years,
- Develop a policy brief that synthesizes key findings from the hydraulic model and translates technical results into adaptable recommendations that support sustainable water management.

### **1.3. Procedure**

The study adopts a modelling-based approach to evaluate the hydraulic performance of Kirke Eskilstrup waterworks by integrating field-collected data, utility records, and operational information into a hydraulic model in MIKE+, which was subsequently calibrated and validated to ensure a reliable representation of the system performance. In addition to the hydraulic assessment, the study includes scenario-based and operational cost analyses to evaluate system behaviour under leakage and high-demand conditions. The study also incorporates a stakeholder value mapping analysis to evaluate how the modelling results may benefit different stakeholder groups.

The overall structure of the report presents the background and theoretical context, methodology, model development, calibration and validation, scenario and stakeholder analyses, discussion of results, and concluding recommendations.

### **1.4. Limitations**

This study is limited to the analysis of the Kirke Eskilstrup water distribution system based on the operational conditions and data available during the project period. As such, the findings may not fully capture long-term system dynamics, seasonal variations, future demand growth, or the impacts of extreme events.

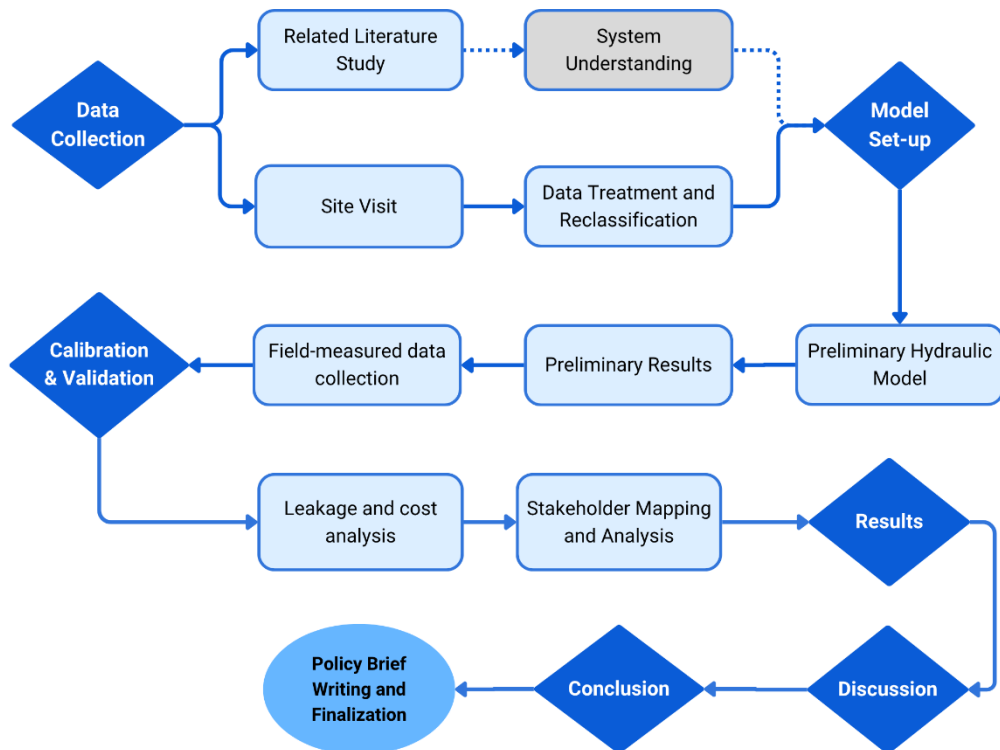
Hydraulic models are inherently simplified representations of real-world systems. To make the system computationally manageable, several assumptions were made. While these simplifications enable the development of the model, they also introduce limitations to its ability to fully capture the complexity of an actual water distribution system. The key assumptions applied in the model are summarized as follows:

- Unknown or missing network parameters (e.g., pipe diameter, material, roughness) were interpolated based on available neighbouring information.
- Minor system components and service connections (e.g., service connection pipes and valves) were excluded from the model.

- System elements, such as water tanks, were represented under idealized conditions (e.g., constant levels).
- Water demand allocation was modelled using time-aggregated water consumption data (e.g., yearly consumption), which was distributed into daily demand and may not capture local demand variations.
- The hydraulic model was initially developed under steady-state conditions, which simplifies the system behaviour by assuming constant hydraulic conditions.

## 2. Methodology

This chapter presents the methodological framework adopted to evaluate the hydraulic model performance and behaviour of Kirke Eskilstrup DWDS. The study combines literature-based analysis, field data collection, geospatial data processing, and hydraulic modelling in MIKE+ to develop a calibrated representation of the network. The methodology was structured to ensure that the model reflects actual operating conditions and provides a basis for scenario evaluation, operational assessment, and stakeholder-oriented analysis. The overall workflow is illustrated in Figure 2.1.



*Figure 2.1 General Workflow Diagram*

Data collection was done in two stages. First, a study of related literature was conducted through a systematic review of academic literature, policy documents, regulatory frameworks, and institutional reports related to water distribution systems and stakeholder governance, which allowed for a better understanding of the system, stakeholder mapping, and value analysis. Second,

a site visit to Kirke Eskilstrup waterworks was conducted for an in-person meeting with the utility and system verification. During the site visit, a meeting with the representative of the water utility was held to obtain information required for the hydraulic model, such as technical characteristics of pipes, valves, pumps, storage facilities, and junctions, operational data, clarify system configurations, and identify any constraints or considerations relevant to the modelling process. This ensures that the model inputs accurately reflect actual operating conditions.

The model set-up phase focused on preparing, processing, and integrating collected datasets into a hydraulic modelling software, MIKE+ 2025. Data collected from the site visit and provided by Ramboll—Pump type, model, and capacity; shapefiles of network components such as pipes, junctions, valves, and tanks; and annual water consumption and consumer information—underwent data treatment and reclassification for easier modelling across different software. The vector data was refined using QGIS, which allowed for easier data sorting, mapping of key components, and integration of terrain elevation data obtained from SCALGO. Because the consumer dataset contained addresses rather than geographic coordinates, the locations were geocoded using the MMQGIS plug-in in QGIS. In addition, AutoCAD was used to digitize and develop schematic diagrams of the distribution network for clearer visualization of the system and its processes.

A preliminary hydraulic model (base model) was developed to simulate the system behavior. The outputs from this initial model produced preliminary results, which helped provide initial insights to identify data gaps and inconsistencies. To improve the model's reliability, field-measured data were collected and used to calibrate and validate the model to ensure that simulated results accurately represent the actual behavior of the water distribution system. Parameters were adjusted iteratively to improve the accuracy of the model. Following the calibration and validation of the hydraulic model, different scenarios were developed to evaluate the system's performance under varying conditions and identify opportunities for operational improvement. A stakeholder mapping and analysis was also conducted to evaluate how the outcomes of the hydraulic modelling and optimization assessment could provide benefits across different identified stakeholder groups.

The findings from the scenario analyses were synthesized in the discussion, wherein the results were interpreted in relation to the study objectives. Finally, the study culminated in policy brief writing and finalization.

### **3. Drinking Water Distribution Systems (DWDS): Performance, Management, and Hydraulic Modelling**

This chapter discusses drinking water distribution systems (DWDS) by reviewing performance, structure, and key challenges such as aging infrastructure, water losses, and increasing pressure from climate change, while acknowledging limitations in current management approaches. This chapter also explores centralized and decentralized systems, highlighting three key dimensions: infrastructure, governance, and operation and maintenance. Drawing on the Danish water sector as a reference, it reviews how regulatory and economic conditions influence system performance. Finally, the chapter presents common optimization approaches and the role of hydraulic modelling in water distribution system analysis.

#### **3.1. Performance Indicators and Challenges**

The supply of safe potable water is heavily reliant on the performance of drinking water distribution systems (DWDS), which have significant effects on both public health and the general welfare of society. The performance of these systems is commonly evaluated using a range of indicators that reflect their efficiency, reliability, water quality, and economic sustainability. Some performance indicators include water losses, service reliability, pressure levels, energy consumption, and cost efficiency (Park et al., 2026). Water distribution systems are susceptible to problems, including pipeline deterioration, aging, and external pollution, because the condition of subsurface pipes affects the water quality. DWDS also depend on the interplay of several components, such as pumps and valves, to function. The water pressure and quality inside the pipes, and the general water flow in the network, are directly impacted by how these components interplay (Park et al., 2026).

Increasing stress on water resources driven by climate change has created the urgent need to enhance water system efficiency and reduce water losses (de Santi et al., 2021). Studies evaluating performance in the water resources management sector are mostly concentrated on managerial effectiveness rather

than sustainability. Decentralized water management techniques, for instance, have been suggested to boost sustainability and resilience. Such decentralized alternatives, according to Leigh & Lee (2019), can strengthen rural water management by connecting communities with limited resources into larger land-use planning (Leigh & Lee, 2019).

Reducing water loss is crucial for sustainable water management as this reduces the negative environmental effects while also reducing the amount of water extracted (Sousa et al., 2025). In addition to the benefits of water conservation, lowering Non-Revenue Water (NRW) not only enhances water quality and service reliability but also makes tariffs more affordable by cutting production costs (Fagundes et al., 2024). The International Water Association (IWA) first introduced the concept of “non-revenue water”, which represents both physical and apparent losses. Physical losses occur when water is lost from the system due to leaks in pipes or reservoirs, never reaching the end consumer. Apparent losses, on the other hand, occur when water is consumed but not billed, often due to defective meters or unauthorized use. While apparent losses do not result in direct water waste, they affect the revenue collected by water utilities (Sousa et al., 2025). Although losses are inevitable in every DWDS, water utility providers must implement strategies to reduce NRW, as it generates significant financial and environmental challenges and indicates operational inefficiency (Amaral et al., 2023). Given the United Nations Sustainable Development Goals (UN SDGs) specifically, Goal 6 of the UN SDGs—providing universal access to clean water and sanitation (United Nations, 2024)—without compromising the significance of other goals, should be a priority for water resources managers, regulators, and the public (Amaral et al., 2023).

## **3.2. Centralized and Decentralized Water Systems**

Centralized and decentralized water systems are often presented as distinct categories, when in reality they exist together rather than as distinct opposites. An example by Cooperman et al. (2025), a “piped town” water supply may be referred to as decentralized as compared to a large or regional network system, which often includes extensive infrastructure and centralized control. The same town system, however, may be considered as centralized when compared to a more localized set-up, such as domestic wells. Moreover, centralization and decentralization are multidimensional concepts that cannot be simplified

to a single aspect. Existing studies in this area often talk about three key dimensions: infrastructure, governance, and operation and maintenance (O&M). These dimensions, which represent the physical, institutional, and functional components of water systems, work together to give a broader foundation for understanding how these systems are structured and managed (Lawhon et al., 2018; Cooperman et al., 2025).

Infrastructure typically refers to the physical components and spatial configuration of the water system, including water sources, treatment facilities, storage, and distribution networks. Centralized infrastructure usually involves large-scale treatment plants and extensive pipe networks that deliver water over long distances, whereas decentralized infrastructure relies on smaller, localized units such as community-scale or on-site technologies (Leigh & Lee, 2019; Stoler et al., 2022). Governance concerns the institutional arrangements, decision-making processes, and distribution of authority among actors. In centralized systems, governance is often concentrated within national or regional authorities, while decentralized systems tend to involve local governments, communities, or individual users (Bakker, 2003; Dobbin et al., 2023). Lastly, O&M often refers to the day-to-day functioning, upkeep, and technical management of the system, such as monitoring water quality, repairing components, and ensuring service delivery, which may be handled by a centralized utility or distributed among local actors, depending on the system design (Bradley & Bartram, 2013).

In Denmark, the drinking water supply is based on a decentralized structure, in which water is generally produced and distributed by numerous local entities rather than by a single large centralized utility. There are approximately 2,600 public waterworks across the country, ranging from small local facilities serving only a few properties to larger utilities serving up to hundreds of thousands of people. Although decentralized in production and distribution, Denmark has national legislation—the Water Supply Act—that governs quality, safety, and standards across all water suppliers (Danish Environmental Protection Agency, 2024). The Danish Water Supply Act (Vandforsyningsloven) is the primary legal framework governing drinking water supply, groundwater abstraction, and municipal responsibilities in Denmark. The law assigns municipalities a central role in regulating water supply systems, ensuring drinking water quality, and overseeing water infrastructure (Danish Ministry of Environment and Food, 2018). In this study, the Kirke Eskilstrup waterworks was regarded as decentralized in infrastructure, centralized in governance, and hybrid in O&M.

### **3.3. The Danish Water Sector Context**

Dansk Vand-og Spildevandsforening, DANVA, is a non-profit organization and functions as a professional network and knowledge platform for utilities providing benchmarking services, statistics, and policy recommendations to support efficient operation and development in the water sector. Data provided by participating utilities are compiled annually in the report *Water in Figures*, which provides key indicators describing operational performance, economic conditions, and environmental impacts of the Danish water sector (DANVA, 2025). The following section draws primarily on the findings presented in the 2025 edition of this report.

#### **3.3.1. Decreasing Water Consumption**

Water consumption in Denmark has shown a long-term declining trend since the introduction of the Action Plan: Aquatic I in 1987, which aimed to reduce nutrient pollution discharges and improve water quality. These initiatives led to increased attention to water use and gradually higher water tariffs due to the expansion of wastewater treatment plants, which in turn encouraged more efficient consumption patterns. In 2024, the average household water consumption reached a historically low level of approximately 97 liters per person per day, corresponding to 35.4 m<sup>3</sup> per person annually. Several factors have contributed to the reduction in water consumption. Danes became more aware of the environmental impacts on the aquatic environment, the mandatory installation of water meters improved monitoring of individual consumption, and technological advancements in domestic appliances, such as efficient washing machines, dishwashers, and low-flush sanitary installations, have reduced water use in households. In addition, the economic effects associated with the COVID-19 pandemic, the war in Ukraine, and inflation in 2020-2021 have encouraged Danish households to pay closer attention to their consumption habits (DANVA, 2025).

#### **3.3.2. Increasing Water Prices in the Future**

Although water consumption has decreased, water prices are expected to rise in the coming decades. According to the water sector forecasts, Danish water utilities will need to invest approximately €114 billion by 2070 in

infrastructure development, climate adaptation, and groundwater protection. These investments include both the construction of new facilities and the rehabilitation of existing water supply and wastewater infrastructure. Since water utilities are fully financed by tariffs, customers cover the costs of operations, investments, and other initiatives (DANVA, 2025).

Climate change is a major driver of these investments, as utilities are already experiencing increased precipitation, rising groundwater levels, and more frequent flooding, thereby requiring both current and future adaptation measures. These can affect drinking water systems by increasing the risk of infrastructure damage, groundwater contamination, and operational disruptions within water supply networks. For instance, extreme weather conditions may place additional stress on aging infrastructure and increase the need for system rehabilitation. Furthermore, protecting groundwater resources is becoming more important due to the growing detection of contaminants such as pesticides and other pollutants. Preventive measures, such as groundwater protection zones and new abstraction sites, require substantial financial resources (DANVA, 2025).

Water tariffs in Denmark vary across the country since they are determined individually by utilities. The sector consists of about 2600 drinking water utilities and around 100 wastewater facilities, each setting its own pricing structure. Danish legislation permits utilities to apply both a fixed annual administrative charge and a variable tariff based on the volume of water consumed for drinking supply, as well as wastewater collection and treatment. Consequently, the calculated volumetric price differs significantly among utilities. Price differences are influenced by structural conditions, including geological characteristics, the scale and composition of the customer base, and other investment needs. Moreover, the drinking water tariff reflects costs associated with groundwater protection, abstraction, treatment, distribution, and quality monitoring from the waterworks to the consumers (DANVA, 2025). While significant investments are expected to drive increases in water prices, the Danish water sector operates under economic regulation that constrains how utilities can recover these costs through tariffs.

### **3.3.3. Economic Regulation**

The Danish water sector operates under an economic regulatory system designed to ensure efficiency while preventing monopolistic pricing. Because

water utilities function as natural monopolies, consumers cannot choose between multiple suppliers. The national regulatory authority sets a revenue cap for drinking water and wastewater utilities that supply a specific volume of water. This cap establishes the maximum allowable income that utilities can collect through tariffs. Utilities may apply for adjustments to the cap if new responsibilities or regulatory requirements impose additional costs. Efficiency requirements are also applied through benchmarking procedures. These include both general productivity targets and individual efficiency requirements based on comparisons between utilities. The objective is to encourage cost-effective operations while maintaining service quality and ensuring necessary infrastructure investments (DANVA, 2025).

### **3.3.4. Non-Revenue Water in Drinking Water Utilities**

In Denmark, NRW levels are relatively low compared with many other countries, with an average water loss of approximately 7%. One of the main drivers behind the reduction of distribution losses has been regulatory measures introduced in the 1990s. Utilities with water losses exceeding the specific threshold were subject to penalty taxation, creating a financial incentive to reduce leakage. As a result, Danish utilities have invested in monitoring technologies, pipeline maintenance, and leakage detection programs. While these investments contributed to low levels of NRW, they also impose ongoing financial and operational challenges, as continuous monitoring and infrastructure renewal are required due to aging pipelines and increasing climate-related stresses affecting leakage levels (DANVA, 2025).

## **3.4. Optimization and Hydraulic Modelling**

According to the European Commission Joint Research Center (2019), pumping systems use the most energy in water delivery systems, frequently making up more than 80% of the total energy use. The energy costs incurred by pumping systems have increased to a considerable portion of the operational costs due to the rising cost of electricity (Brás et al., 2025). Optimization of energy costs can be carried out by reducing network leakage, altering the pumping operations, modernizing the pipe network, and using computer

modeling simulations for network operation changes (Świętochowska & Bartkowska, 2022).

Pressure management is another essential approach for controlling water losses in a distribution system, as the leakage flow rates are strongly influenced by pressure levels. It involves regulating water pressure in the network to make sure it is neither too low nor too high, as higher pressure increases the flow rate of leaks and the likelihood of pipe bursts (Tian et al., 2023). Even though pressure management techniques have been successfully applied in some regions of the world, other research suggests that it may be challenging to apply in developing countries, where socioeconomic problems exist, such as theft, unauthorized connections, poverty, etc. (Mathye et al., 2022).

The use of Pressure Reducing Valves (PRV) is a common method, as they help stabilize pressure in specific zones of the network. This not only reduces leakage volumes but can also decrease the frequency of pipe bursts and associated operational costs. Several studies have shown a clear correlation between the use of PRVs in leakage control and a decrease in operational costs (Tian et al., 2023).

Pump schedule optimization is a useful strategy for lowering operational expenses and managing network pressure while offering consumers dependable water supplies. Water utility companies can increase the overall efficiency of WDSs and save energy by taking into account the most suitable times of pump operation (Shao et al., 2024).

Over the past two decades, there has been a significant interest in computerized optimization of DWDS. The usage of computer software for water distribution systems has increased in recent years, which is consistent with the increasing demand for improvements in operational efficiency. In most cases, hydraulic modeling has been used to help estimate leaks in the network, monitor and evaluate the water quality, and analyze the system's capacity for future developments (Alsaydalani, 2024).

Rossman's (2000) EPANET hydraulic model is an essential tool for understanding the current status of water distribution systems and predicting their performance under different conditions. By developing stochastic scenarios for various demand patterns, it can assist with managing network uncertainties. Correct predictions of system performance using such tools can significantly help improve efficiency and promote sustainable water management (Dadebo et al., 2023).



## 4. Model Set-up and Implementation

### 4.1. General Settings

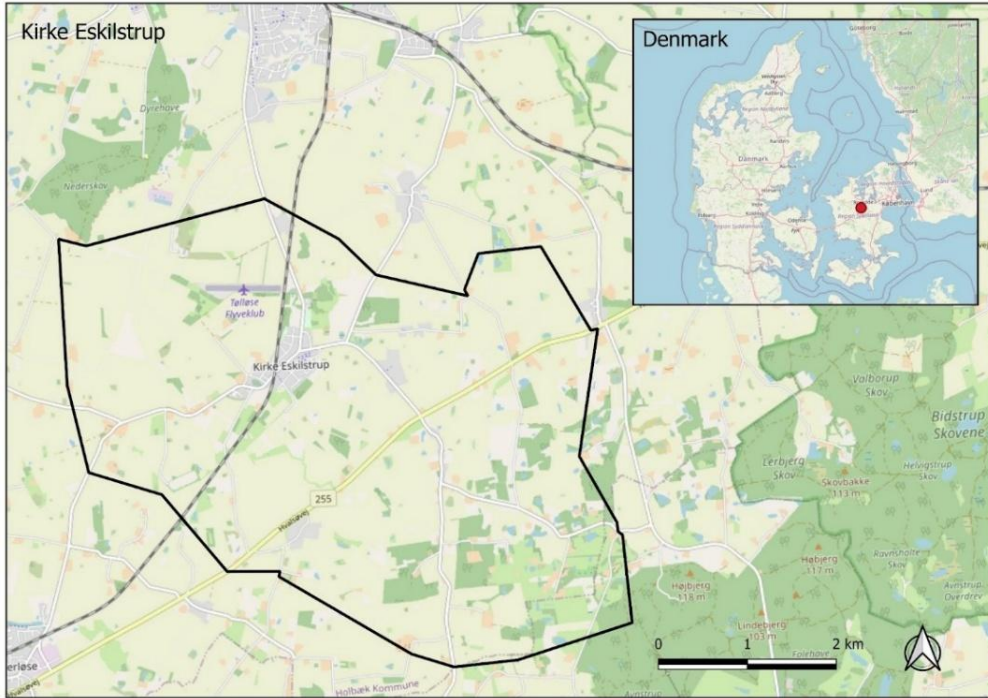
This study utilized an integrated water modelling software called MIKE+ 2025. This software incorporates hydraulic simulation engines, network analysis functions, and scenario management tools to simulate, analyze, and manage complex water systems, including pipe networks, rivers, and surface flooding. Its water distribution modelling module, based on EPANET 2.2, allows detailed hydraulic and water quality modelling and simulations of DWDS, supporting scenario evaluation, network optimization, and the identification of operational issues such as leaks or pressure inadequacy (DHI Group, n.d.). The software license was obtained through the DHI Student Lab kit. Head losses were calculated using the Darcy-Weisbach formula under steady-state conditions for preliminary model checks. All data necessary for modelling were provided by Ramboll and the water utility. The general settings are presented in Table 4.1.

*Table 4.1. General Settings*

<b>Model Type</b>	Water Distribution
<b>Coordinate System</b>	ETRS89/UTM Zone 32, Northern Hemisphere
<b>EPANET Engine</b>	DHI EPANET 2.2
<b>Head Losses</b>	Darcy-Weisbach formula
<b>Module</b>	Steady-state conditions

### 4.2. The Study Area

In 1901, Kirke Eskilstrup became a station town following the construction of the Høng-Tølløse railway line. It is situated in Holbæk Municipality, Region Zealand, Denmark, approximately 18 km South of Holbæk and 20 km North of Ringsted, making it part of the agricultural hinterland of central Zealand (KE Vand, n.d.).



*Figure 4.1. Kirke Eskilstrup - Study Area*

The town has a moderate population, with approximately 600 consumers connected to the distribution network during the study period. This relatively small population indicates that seasonal tourism and vacation homes do not significantly influence water demand patterns, unlike in many coastal or summer-house regions of Denmark, where seasonal variation significantly affects water consumption. The town sits within a predominantly rural and agricultural landscape, consisting of residential houses and some small businesses. Agricultural land-use dominates the area, such as pig farms taking up about 23% of the total water supply.

The local water utility, Kirke Eskilstrup Waterworks, serves the town's drinking water supply. It was established in the 1930s as a cooperative, the waterworks was designed to provide adequate, clean water to its members. The waterworks currently generates about 80,000 m<sup>3</sup> of water yearly, where the quality is closely monitored (KE Vand, n.d.). The most recent infrastructure upgrade took place in 2025, during which approximately 1 km of pipeline in

the town center was renovated. No incidents of soil contamination or water quality issues were reported prior to this study. The waterworks is linked to Store Merløse Waterworks and Kvarmløse-Tølløse Waterworks, which are all linked to Ugerløse Waterworks. Thus, the four waterworks create a ring connection that can sustain the water demand in the case of pollution, repairs, power outages, etc. (KE Vand, n.d.).



*Figure 4.2. Kirke Eskilstrup Waterworks Pump Station/Office*

All consumers are equipped with digital water meters, and consumption data is collected quarterly using a drive-by method and automatically sent to their database called FAS. Additionally, the waterworks uses RambollGraf; therefore, the water network is easily accessible for viewing through the website. The spatial layout of the Kirke Eskilstrup distribution network is illustrated in Figure 4.3.



*Figure 4.3. Kirke Eskilstrup Distribution Network*

### **4.3. Pipe Network**

The pipe network was modelled as the main hydraulic conveyance system, with geometric and material properties defined to accurately simulate flow and pressure dynamics within the distribution system. Ramboll provided GIS shape files that contain information, such as the type of pipe, diameter, material, year of construction, etc. The dataset contains features that are not part of the study area; therefore, those features were deleted. Additionally, some pipe types that were not relevant in the modelling process, such as minor pipe branches (service connection pipes, decommissioned pipes, and surveyed pipes), were disabled in MIKE+.

Based on the Danish Standard, DS 439 Code of practice for domestic water supply installations, drinking water pipes installed in soil should be buried at a depth of at least 1.2 meters below ground level to prevent frost damage to the

system (Danish Standards, 2009). All pipes in the network are assumed to be buried at a depth of 1.2 meters below ground level. This burial depth has also been adopted in previous hydraulic modelling studies of Danish drinking water distribution systems (Cifuentes Meza, 2024; Stagne & Svantesson, 2023).

#### 4.3.1. Diameter

The pipe diameter is a key parameter for hydraulic modeling of DWDS, as it affects velocity, pressure, and head loss (Desta et al., 2022). Some pipe diameter attributes in the geospatial vector data were missing; in total, 500 pipes lacked diameter information. Of these, 309 are service connection pipes, which were disabled in the model. Therefore, to account for the missing data, an interpolation was performed in the remaining 191 pipes in MIKE+, which essentially assigns values to null fields based on the neighboring pipe diameters. While this approach provides reasonable estimates, the interpolated values introduce some uncertainty into the model results. The dimension of the pipes varies from Ø160 for the outgoing pipes, Ø110 for the transmission pipes, to Ø50 for the service pipes. The distribution of the pipe diameters can be seen in Figure 4.4.



Figure 4.4. Distribution of Pipe Diameters

The pipe wall thickness is a required parameter in MIKE+ as it contributes to the hydraulic representation of pressurized pipe behavior within the model calculations (DHI, n.d.). It was not specified in the aforementioned dataset; therefore, it was estimated based on the dimensional information provided in the product catalogue of one of the pipe manufacturers in Europe, Wavin. The wall thickness was calculated from the outer diameter and standard dimension ratio (SDR) values (Wavin, n.d.), listed in Table 4.2.

*Table 4.2. PE Pipes Wall Thickness*

<b>Pipe Diameter (mm)</b>	<b>Wall Thickness (mm)</b>
32	2.0
40	2.4
50	3.0
63	3.8
75	4.5
90	5.4
110	6.6
160	9.5

#### **4.3.2 Materials**

The distribution network consists mainly of plastic pipes: Polyethylene (PE) and Polyvinyl Chloride (PVC). About 50% of the network is of PE material, and 50% of PVC, according to the water utility representative. As can be observed from Figure 4.5, the pipes are of PE material starting from the pump station and throughout the main town. While the pipes extending out of the town are of PVC material. Similar to the pipe diameters, some pipe materials were also missing and were therefore assumed to be the same material as the neighboring pipes.

Since the 1950s, plastic pipes have become popular and widely used in drinking water networks due to their advantages compared to concrete and alloy pipes. Plastic pipes are more flexible and resistant to mechanical damage, simpler to install, and most importantly, do not corrode (Świetlik & Magnucka, 2025). The distribution of the pipe materials can be seen from the figure below.



*Figure 4.5. Distribution of Pipe Materials*

### 4.3.3 Roughness

Pipe roughness coefficients change with time as a result of scaling, biofilm formation, and material aging. Therefore, roughness coefficients in hydraulic models are often estimated using pipe age as an indirect indicator. Continuous operation of the distribution pipes, material type, and water chemistry all contribute to the increase in pipe wall roughness and surface deterioration, which affects hydraulic resistance. Simulated and actual pressures in water distribution networks can differ significantly if roughness variations are ignored. Thus, it must be adjusted during calibration to provide correct and reliable hydraulic simulations (El-Ghandour et al., 2021; Kaltenbacher et al., 2022; Zhao et al., 2022).

The roughness values were estimated based on the provided look-up table in MIKE+. Using the Darcy-Weisbach equation, roughness coefficients in the range 0.005-0.025 mm for Plastic(min) and Plastic(max), respectively, were selected for plastic pipes.

## 4.4. Valves

The distribution network contains 218 valves, consisting of shut-off valves and service connection valves. In the hydraulic model, the service connection valves, which account for 139 valves, were disabled because the associated service pipes were also excluded from the simulation. Consequently, only the main network valves were retained active to represent operational segmentation and flow control within the network.

All of the remaining 79 active valves were modeled as General Purpose Valves (GPV) with locked-open status (fully-opened), since there was no valve opening-closing plan provided by the waterworks. All active valves were assumed to be fully functional and operating under normal conditions considered in the modelling scenario.



*Figure 4.6. Valves within the Water Network*

## 4.5. Topography

The study area is situated on a generally even level terrain. The topographical data was obtained from SCALGO, a digital platform that provides detailed terrain and surface water data (Scalgo, n.d.). A Tag Image Format (TIF) file of the study area was downloaded and used to identify the elevation of the network elements, which is an important input when modelling a DWDS.

The topographical profile in Figure 4.7 shows elevation differences across four transmission profiles. The pump station located near the town center supplies the network, while two booster pumps are positioned along the distribution network to support pressure in hydraulically disadvantaged zones. An upward elevation trend in Profiles 2 and 3 requires additional pumping energy to maintain adequate pressures; thus, two booster pumps are placed along these directions. In contrast, Profile 1 shows fluctuations in elevation, while Profile 4 has a descending trend.

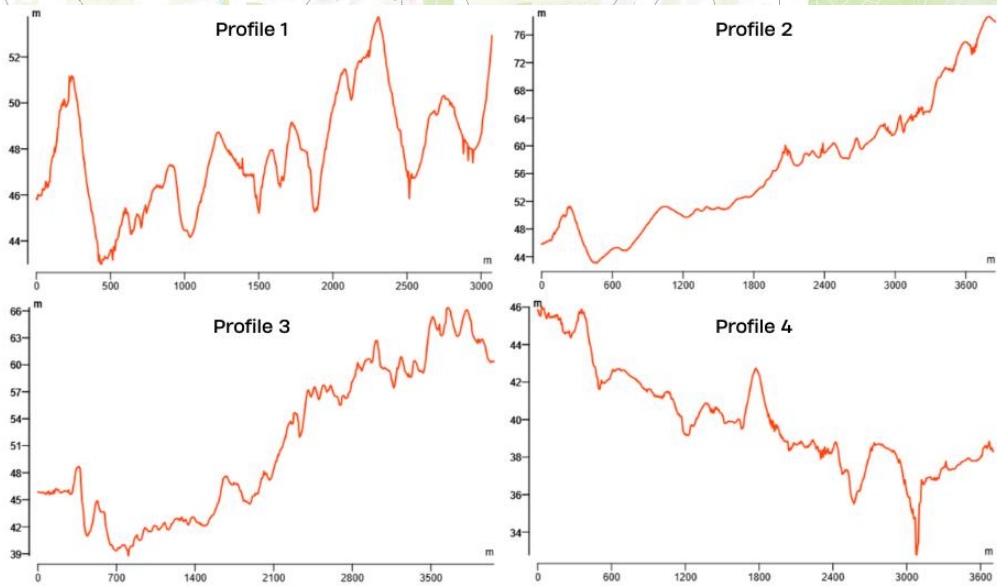
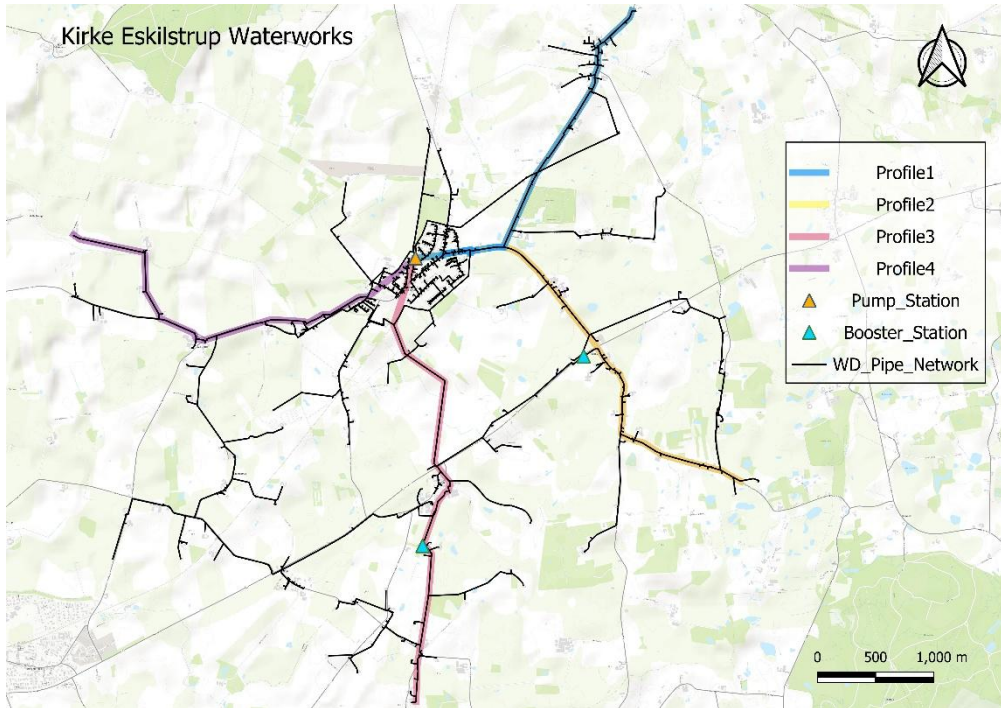


Figure 4.7. Topographical Profile of the Kirke Eskilstrup Waterworks

## 4.6. Pump Station

The waterworks' pump station is located near the town center of Kirke Eskilstrup. To ensure the quality of drinking water, the waterworks carry out a simple water treatment by oxygenating the water and filtering it through sand filters. Water quality is monitored in accordance with the Drinking Water Executive Order to ensure consistent compliance with regulatory standards. A minimum of four drinking water samples are obtained from each borehole every four years and tested for the parameters: microbiological (coliform bacteria, *Escherichia coli*, and enterococci) and physico-chemical (iron, manganese, nitrate, water hardness, and selected pesticides) to assess raw groundwater quality. Analyses are conducted both prior to distribution from the waterworks and at consumers' taps to verify water quality throughout the supply system (KE Vand, n.d.).

### 4.6.1. Main Pumps

The pump station has four parallel pumps, which are approximately 8-10 years old. All pumps have the same model, Grundfos CR 15-5 A-F-A-E-HQQE, which is a vertical, multistage centrifugal pump (Grundfos, n.d.-a). In the model, the pump type was set to Variable Speed Drive (VSD) pumps with a specific pump curve obtained from the pump manufacturer. During the initial simulation, two pumps were active, and the other two were inactive based on the scenario at the waterworks live monitoring system. Blue Control is a Danish technology provider that develops SCADA (SRO) systems with centralized control, real-time data acquisition, and remote access for automation and monitoring solutions (Blue Control A/S, n.d.). The two inactive pumps will operate when the demand flow is above the capacity of the two operating pumps. The service pressure from the waterworks is set to 4.0 bar.

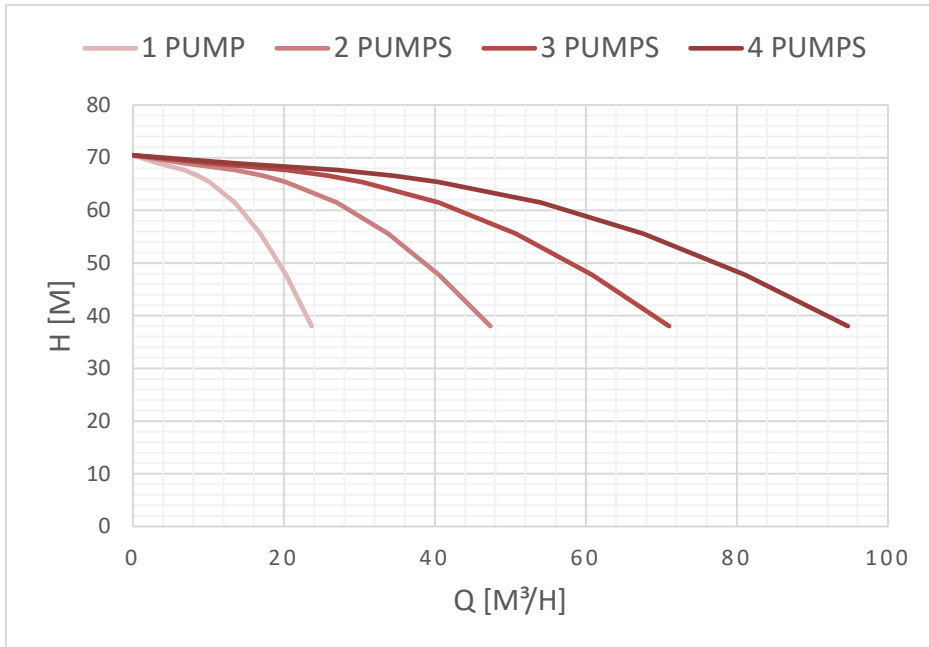


Figure 4.8. Pump Curve, 4-Parallel Pumps at Waterworks

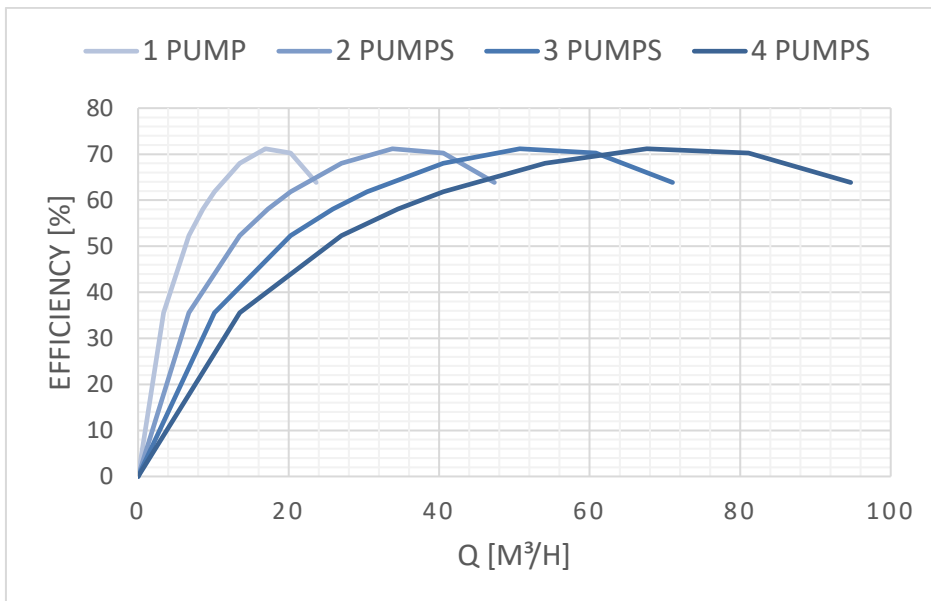


Figure 4.9. Pump Efficiency Curve, 4-Parallel Pumps at Waterworks



*Figure 4.10. Four Parallel Pumps at the Waterworks*

### **4.6.3. Tanks**

The waterworks has two storage tanks with volumes of 80.2 m<sup>3</sup> and 87.8 m<sup>3</sup>. Four boreholes with a depth of roughly 28–65 meters are used to pump up all of the water that is stored in these tanks. In the hydraulic model, the storage tank was represented as a fixed-level reservoir with a constant hydraulic grade line (HGL). This configuration assumes an infinite and continuously available water source throughout the simulation period.

### **4.6.2. Booster Pumps**

The distribution network has two booster pumps placed along the system towards the Eastern and Southern areas of the network, located at Hvalsøvej and Birkegårdsvej, as can be seen from Figure 4.7. The booster pumps are from Grundfos with model CRE10-03 A-A-A-E-HQQE and CRE5-9 A-A-A-E-HQQE (Grundfos, n.d.-b; Grundfos, n.d.-c), and have a service pressure of 5.1 bar and 4.5 bar, respectively. In the model, the booster pumps were also set

as VSDs with a corresponding pump curve obtained from Grundfos. The pump curves of the two booster pumps are illustrated in Figure 4.11.

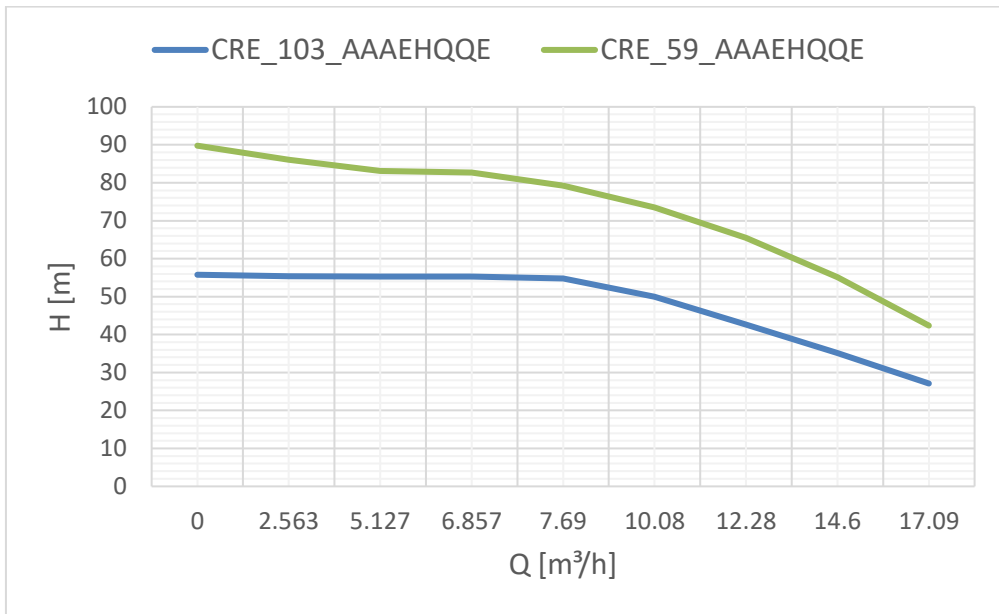


Figure 4.11. Pump Curve, Booster Pumps 1 & 2

## 4.7. Water Demand

The consumer data provided by Ramboll from the FAS database contains information such as annual consumption, consumer type, address, water meter ID, etc. Since the demand must be assigned specifically to each consumer, the raw consumption data was processed using QGIS by geocoding the consumer's address and converting it into coordinates using the plug-in MMQGIS. After geocoding, a vector shape file was generated containing the points representing each consumer.

In the hydraulic model, each consumer point was used to define demand allocations within the network. Since the service pipes and associated service valves were disabled in the model, individual consumer demands were assigned to the nearest active distribution node. These demands were subsequently aggregated at the nodal level, ensuring that consumptions were appropriately represented within the distribution system.

The obtained consumption data were provided on an annual basis and were subsequently distributed into average daily consumption values in the model. To represent variations in water use, the daily consumption was adjusted using demand factors associated with specific consumer types and their respective consumption patterns. These demand factors are discussed in more detail in Section 4.7.2.

#### 4.7.1. Consumer Types

Kirke Eskilstrup is a small town located in a predominantly agricultural region of Denmark. The water demand within the study area is primarily associated with residential households, agricultural activities, and a limited number of small businesses/institutions. Consumption data for the year 2025 were provided by Ramboll and comprised 605 registered consumer records connected to the distribution network.

The residential users constitute the dominant consumer category, accounting for about 75% of the total annual consumption. Agricultural demand is mainly attributed to four pig farms located within the study area, and a small portion of the total annual consumption corresponds to minor commercial activities. The consumers were categorized into Residential, Agricultural, and Commercial to define the demand categories in the hydraulic model.

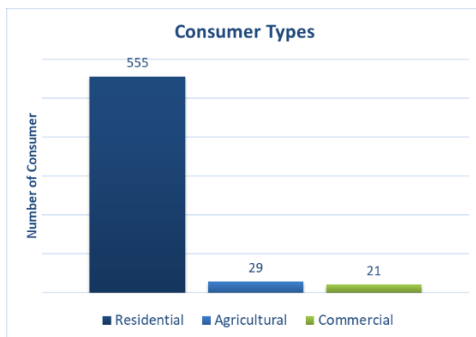


Figure 4.12. Consumer Types

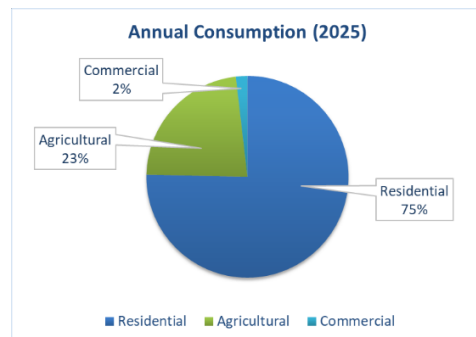
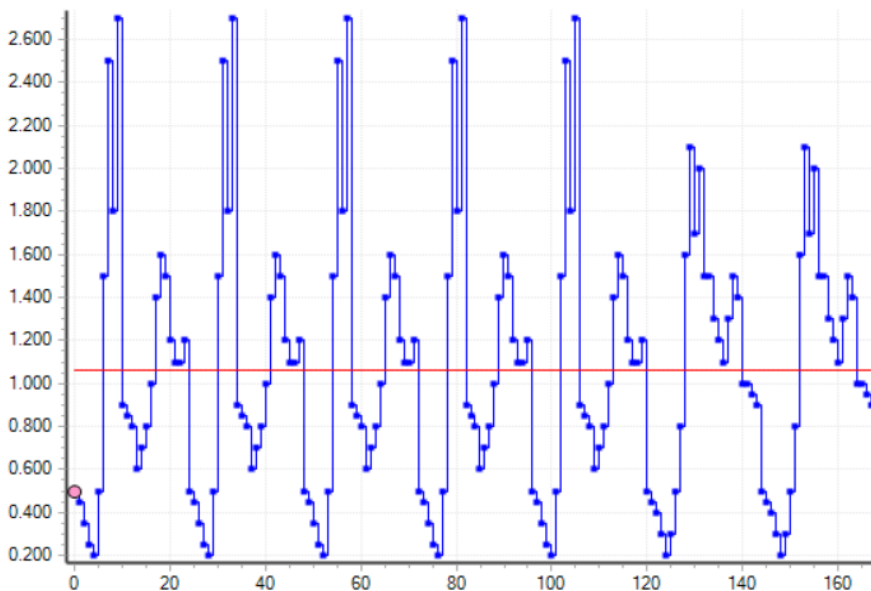


Figure 4.13. Annual Consumption (2025)

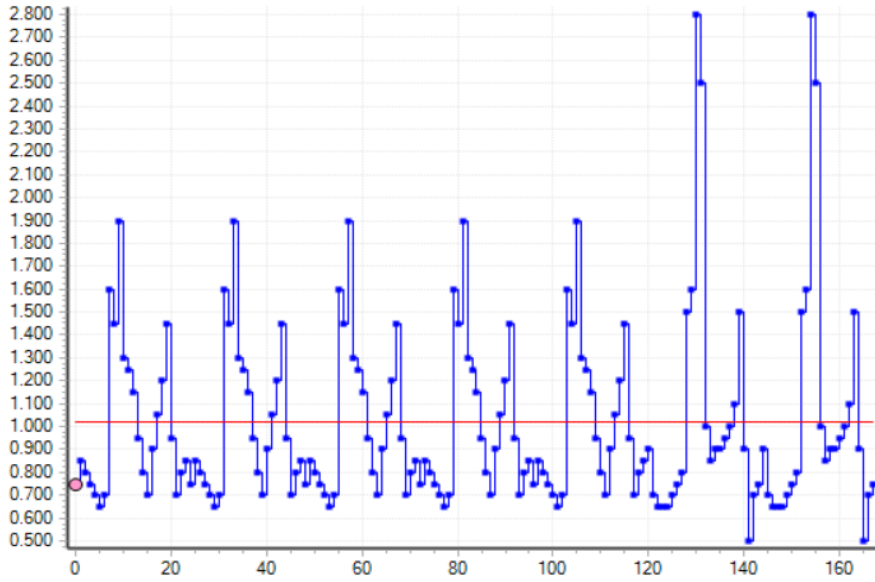
### 4.7.2. Demand Patterns

To represent variations in water consumption, demand patterns were assigned to the different consumer categories in the model. The standardized demand patterns were obtained from Miljøprojekt nr. 998 (Miljøstyrelsen, 2005), which provides representative demand patterns for different types of consumers.

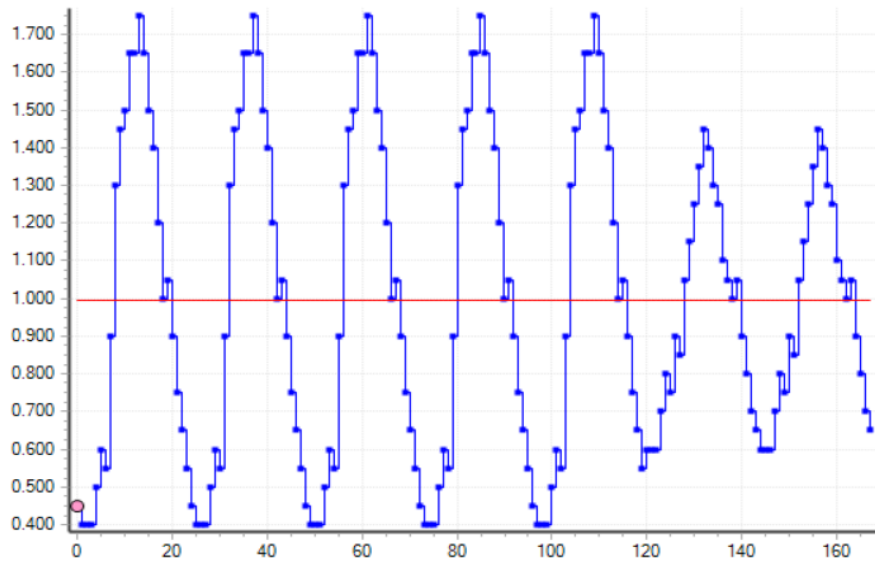
The demand patterns describe the relative variation of water consumption over time and are expressed as dimensionless scaling factors. A scaling factor greater than 1 indicates demand above the average flow, while values below 1 represent periods of reduced consumption (Rossman et al., 2020). In the demand curves, the y-axis represents the scale factor relative to the average flow rate, while the x-axis represents the simulation time steps in hours for a 7-day period.



*Figure 4.14. Demand Pattern for Residential*



*Figure 4.15. Demand Pattern for Agricultural*



*Figure 4.16. Demand Pattern for Commercial*

## 4.8. Preliminary Simulation Result

The preliminary simulation was performed under steady-state conditions to provide an initial overview of the system's hydraulic behaviour before calibration and validation. The spatial distribution of pressure (m) at nodes and flow (l/s) through the links, as illustrated in Figure 4.17, indicates variability across the network. Higher pressures were observed near the central part of the network, while a potential weak zone was identified in the northern part. These patterns were expected at this stage due to uncertainties in demand allocation, pipe roughness, and boundary conditions.

Several topology checks were performed to ensure that the network configuration was correctly represented and free from major connectivity issues. Demand allocations were also reviewed to verify the water balance within the system and to confirm that the assigned demands were consistent. Following the overall assessment of the preliminary result, the calibration and validation procedure was prepared for the next stage of the study.

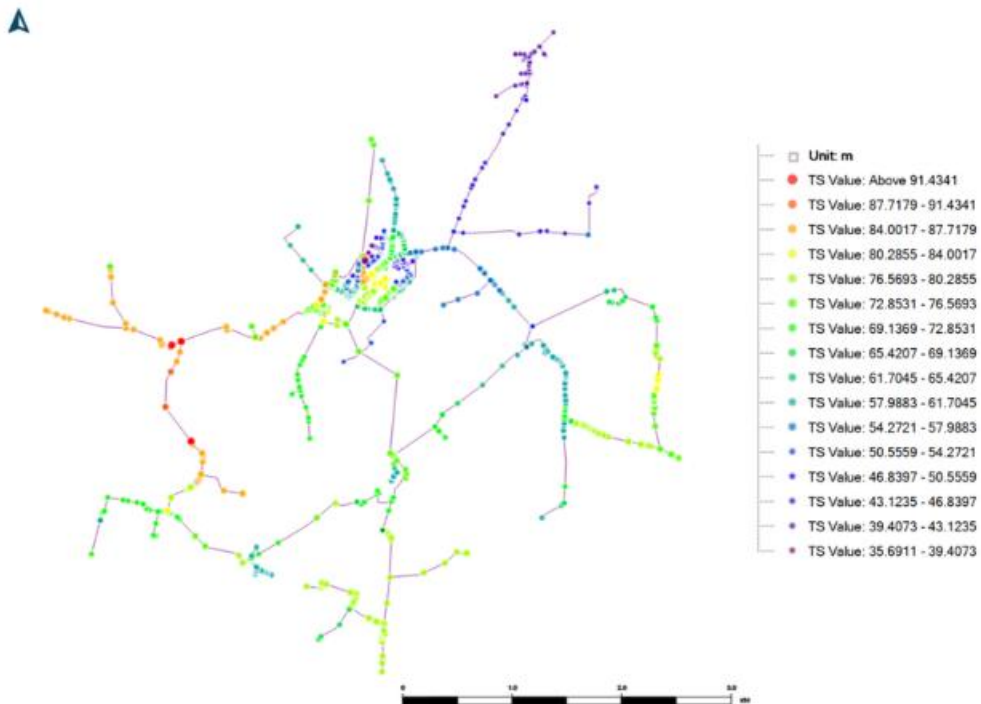


Figure 4.17. Head (m) at junctions and Flow (Absolute) (l/s) through links

## 5. Calibration and Validation

### 5.1. Data Collection

The data used for the model calibration were collected using four KELLER LEO Record pressure loggers, shown in Figure 5.1. Field measurements were conducted over seven days, from 16 April to 23 April 2026, with a recording interval of 5 minutes. All pressure measurements were recorded in mbar.

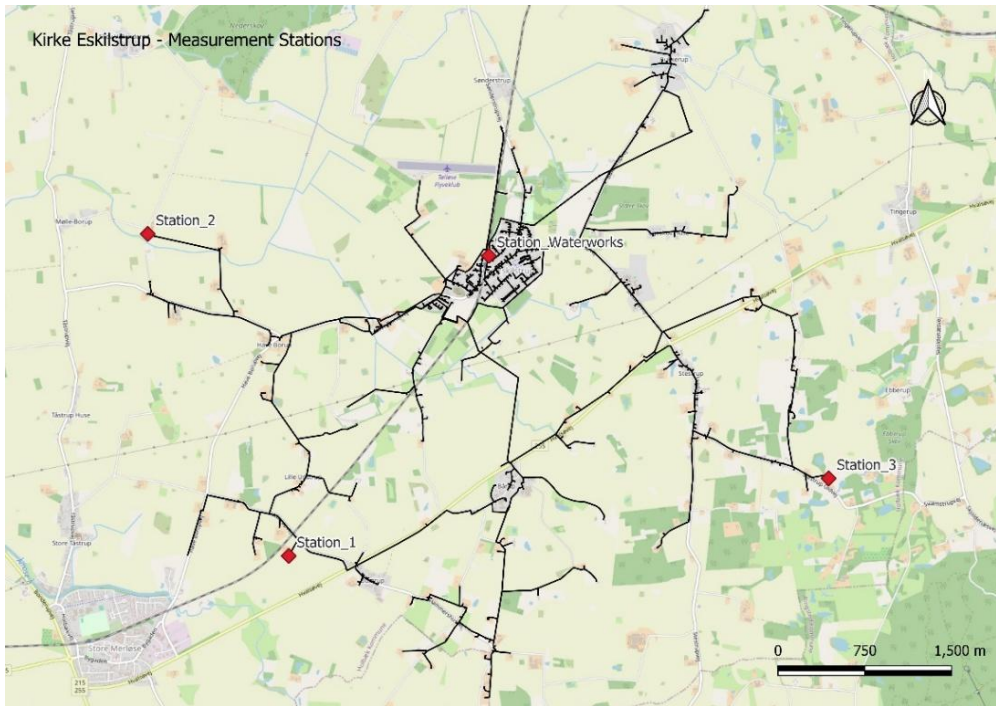


*Figure 5.1. Pressure Loggers*

The pressure loggers were installed at different locations within the distribution network, as listed in Table 5.1. Due to the unavailability of fire hydrants in the distribution network, the loggers were instead installed on consumer properties. However, due to technical issues, only three of the four loggers successfully recorded data. At Stations 1, 2, and 3, only pressure data were available, whereas both flow and pressure were obtained from the waterworks real-time monitoring system, BlueControl. The locations of the data loggers were chosen strategically to represent conditions in the network and are shown in Figure 5.2.

*Table 5.1. Pressure loggers Station, ID, and Locations*

<b>Station</b>	<b>Logger ID</b>	<b>Address</b>	<b>Data</b>
<b>Waterworks</b>	Blue Control	Plantanvej 1B	Flow, Pressure
<b>Station 1</b>	1_10654	Udstrupvej 44	Pressure
<b>Station 2</b>	2_10650	Enghavej 28	Pressure
<b>Station 3</b>	3_11723	Stestrup Oldvej 51	Pressure



*Figure 5.2. Measurement Stations*

The data stored in the loggers was extracted using the Keller LOGGER 5 software, after which the data were converted into Excel (XLS) format and exported for further processing. In addition to field measurements, flow and pressure data from the waterworks were obtained from the BlueControl. These datasets were used as input for generating time series within the model, using MikeZero, for the calibration and validation stages.

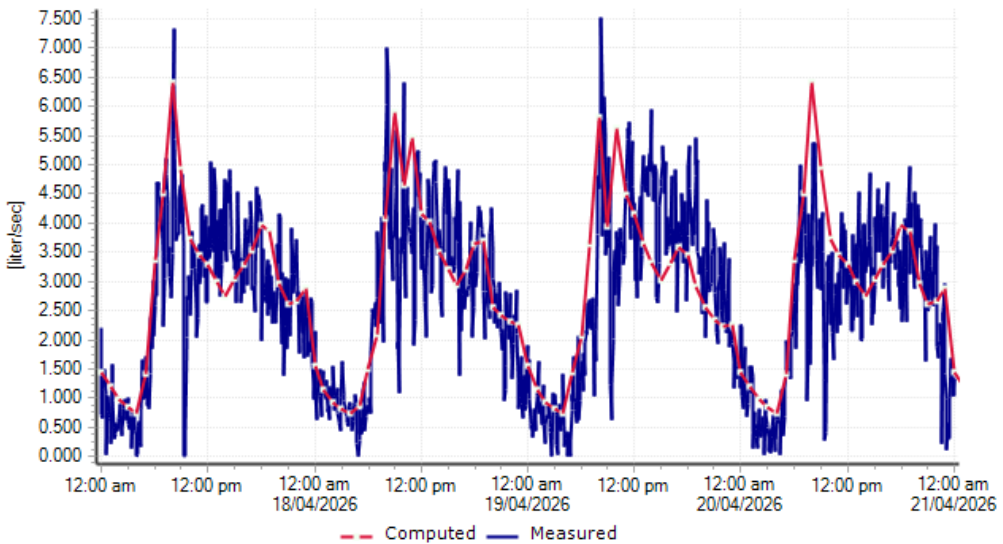
## 5.2. Calibration

The calibration of the model was undertaken using data obtained from the pressure loggers and the BlueControl system. The dataset was divided into two subsets, with 70% allocated for calibration, and the remaining 30% was reserved for the validation procedure. The data from the pressure loggers were resampled, and only the days with a full 24-hour period were considered, which is from 17 April 00:00:00 to 23 April 00:00:00. Therefore, to capture the diurnal behavior of the model, four days were allocated for calibration (Friday to Monday) and the remaining two days (Tuesday and Wednesday) for the validation procedure.

Calibration and validation simulations were performed under the Extended Period Hydraulic (EPH) module, configured to match the time frame, date, and temporal resolution of the field measurements, to ensure consistent comparison between measured and computed values. Before adjusting calibration parameters, the operational inputs were checked and corrected, including measurement station locations, node elevations, pressure datum consistency, valve operating status, closed and open loops, and demand allocations. These checks were necessary to avoid using calibration parameters to compensate for incorrect data or operational assumptions.

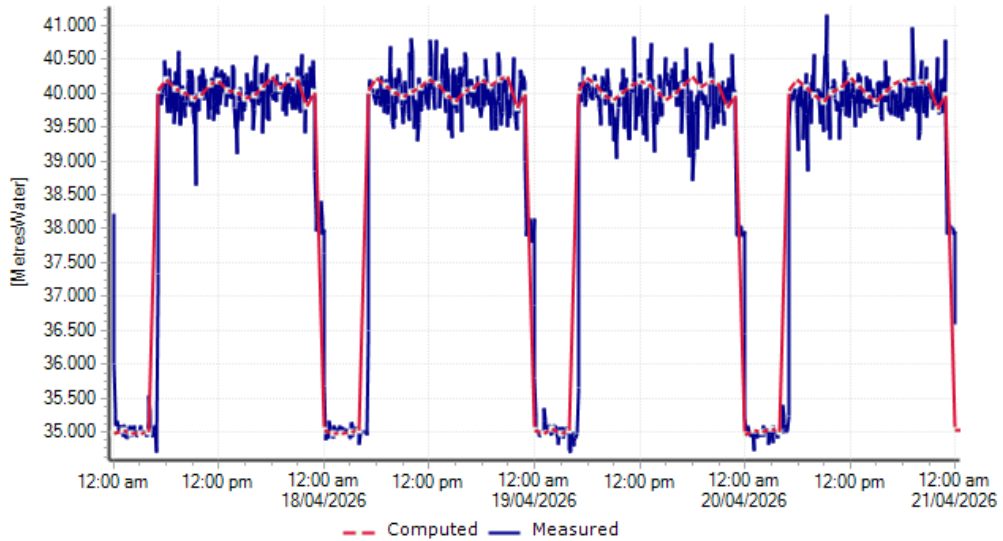
After these corrections, the model showed a reasonable agreement with the measured waterworks pressure and captured the general daily flow pattern. This indicated that the source boundary conditions and overall demand allocation were sufficiently represented. The calibration was then performed under current operating conditions by iteratively adjusting model parameters, including pipe roughness coefficient, valve head-loss setting, demand pattern coefficient, and pump operational settings, to achieve an optimal match between the measured and computed values. Model calibration was primarily evaluated using visual fit assessment, where the agreement between measured and computed graphs was based on the similarity of trends, peaks, and overall pattern. The detailed calibration procedure is discussed below.

To improve the agreement between the computed and measured graphs, the first comparison was made using the waterworks flow graph. Some coefficients in the consumer demand pattern were adjusted to better match peak demands and balance the total system demand by comparing the general statistics of the measured and computed values, provided in the calibration module of the software. The calibrated result for the waterworks flow measurement is presented in Figure 5.3.



*Figure 5.3. Calibrated Measurements: Waterworks, Flow (l/s)*

The next comparison was made using the waterworks pressure graph. The computed values followed the average pressure trend of about 40 mWC due to its set control pressure. However, the measured values illustrated a shift during low hours (00:00:00 to 5:00:00), therefore, the pump operational setting was adjust to match the 35 mWC during low hours and 40 mWC during normal hours. The calibrated result for the waterworks pressure measurement is presented in Figure 5.4.

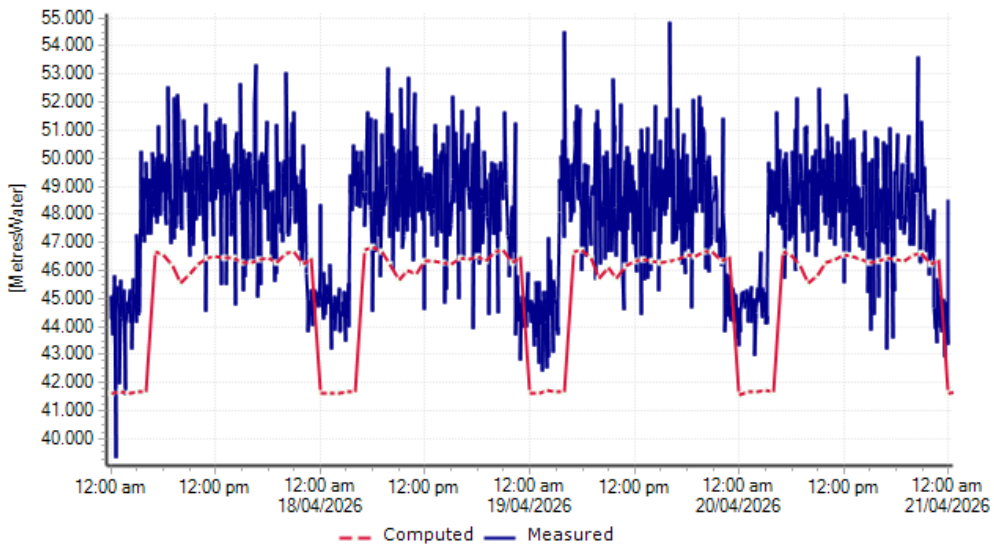


*Figure 5.4. Calibrated Measurements: Waterworks, Pressure (mWC)*

After calibrating the waterworks flow and pressure measurements, the computed pressure graphs at the other three monitoring stations generally followed the measured pressure trends, although slightly lower. The distribution of head loss across the system was then evaluated to further enhance the accuracy.

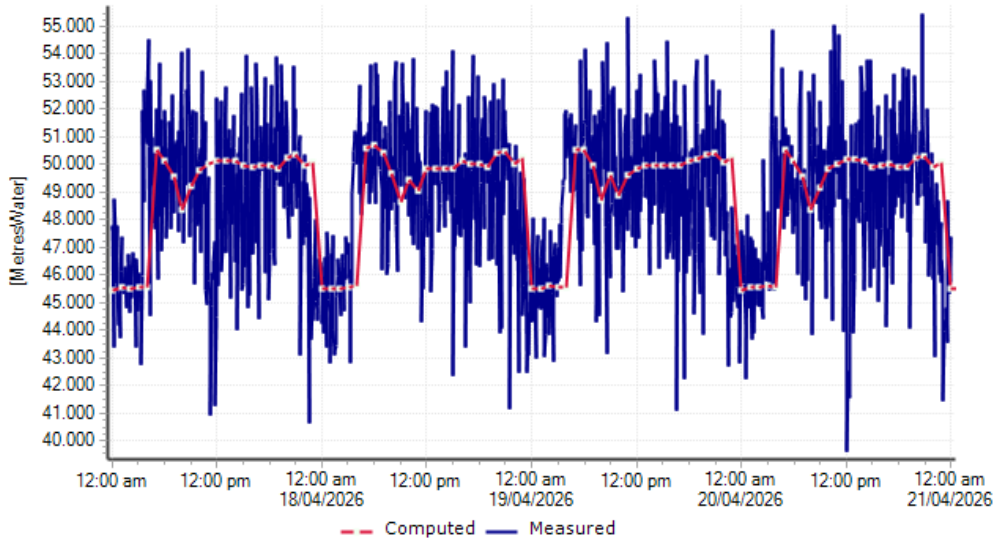
Calibration groups for pipe roughness were identified by hydraulic function, diameter, and year of construction. The groups were identified as main distribution pipes ( $\text{Ø}160\text{mm}$ ), primary distribution pipes ( $\text{Ø}110\text{-}\text{Ø}90\text{mm}$ ), and secondary distribution pipes (less than  $\text{Ø}75\text{mm}$ ), and sorted based on the pipe construction year. Manual iterative calibration was performed by adjusting the roughness values for these pipe groups. The direction was based on the pressure response observed in the graphs, where simulated pressure was lower than measured, the model was assumed to be creating excessive head loss along the flow path. Station 1 showed a remaining pressure difference; therefore, an additional targeted group was created for the main supply path influencing that measurement station.

Each calibration run was assessed using the same set of comparisons: the waterworks pressure graph as a control check, as it represents the source boundary condition; the waterworks flow graph to confirm that the overall demand pattern was not degraded during roughness adjustments; and the three measurement stations to assess whether the internal head-loss distribution improved. Calibration targets were based mainly on reducing systematic pressure bias while maintaining the correct overall flow and pressure trends, rather than overfitting short-term spikes and measurement noises. The calibrated results for measurement Stations 1-3 are presented in Figures 5.5 to 5.7.



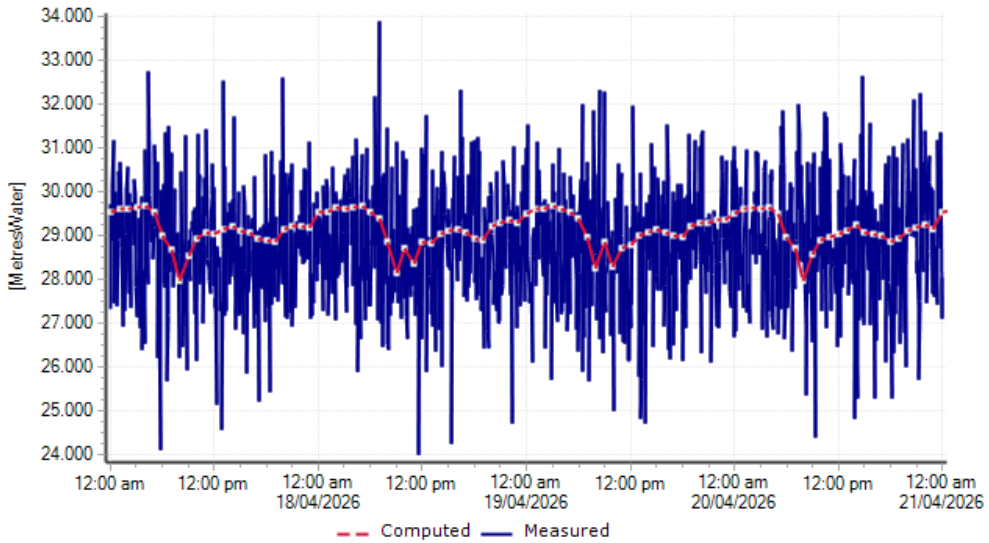
*Figure 5.5. Calibrated Measurements: Station\_1, Pressure (mWC)*

The simulated pressure at Station 1 remained slightly lower, about 2-3 meters, than the measured pressure. A likely explanation is that the discrepancy is not solely due to pipe friction losses, but also the difference between real system behaviour and the simplified hydraulic conditions represented in the model. For instance, the pressure logger was installed in a private area, while in the model, it is represented at the nearest main distribution pipe node. In addition, the ground elevation assigned to the model was derived from the available DEM, which may not capture local elevation variations or the exact tapping elevation of the logger.



*Figure 5.6. Calibrated Measurements: Station\_2, Pressure (mWC)*

Station 2 shows a good overall agreement between computed and measured pressure values. The model captures the daily pressure pattern, including the low-hour period. In contrast, Station 3 shows a reasonable match in average pressure level, but does not follow the daily pattern. It is worth noting that Station 3 is located at the end of the southeast branch of the network, where pressure is influenced by a booster pump without the same pump setting as the pumps in the waterworks. Therefore, the measured pressure pattern is likely due to local effects that reflect local conditions in this area.



*Figure 5.7. Calibrated Measurements: Station\_3, Pressure (mWC)*

### 5.3. Validation

The calibrated model was subsequently validated using the remaining 30% (two days) of the dataset presented in Figures 5.8 to 5.12. This independent dataset provided a basis for assessing the model’s performance under conditions not explicitly fitted during calibration. Model outputs were compared against the corresponding data to ensure acceptable accuracy before performing further analysis.

Overall, the measured and computed flow and pressure graphs showed a reasonable agreement in both trend and magnitude, suggesting that the calibrated model was able to represent the main hydraulic behavior of the system. The remaining differences were mainly short-term fluctuations and local measurement effects, rather than systematic model error. Therefore, no further parameter adjustments were made during the validation procedure.

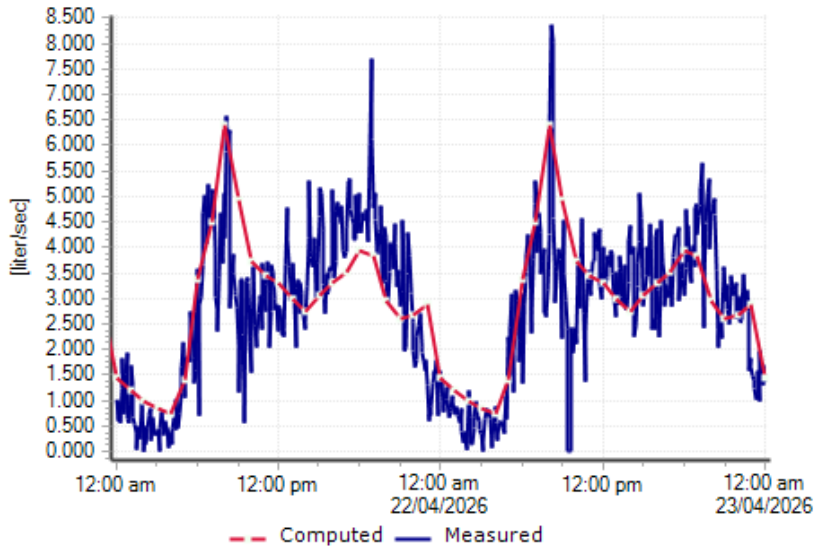


Figure 5.8. Validated Measurements: Waterworks, Flow (l/s)

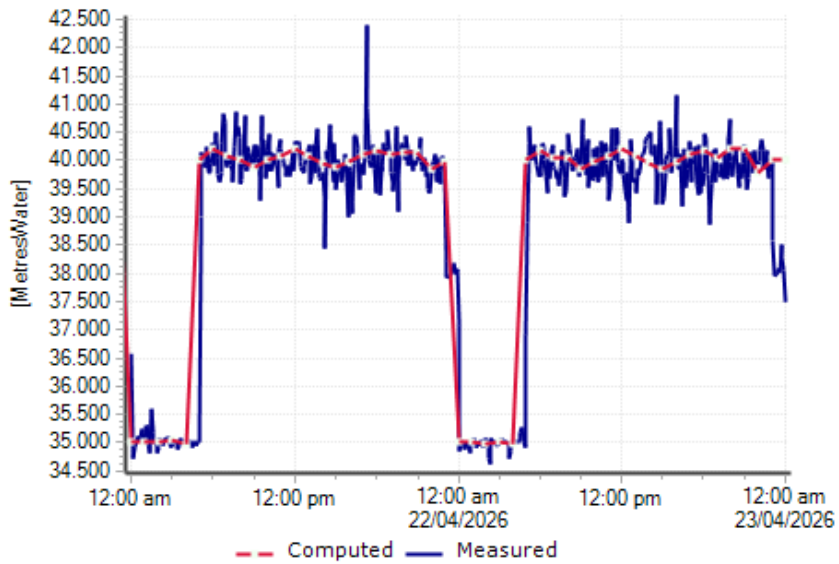


Figure 5.9. Validated Measurements: Waterworks, Pressure (mWC)

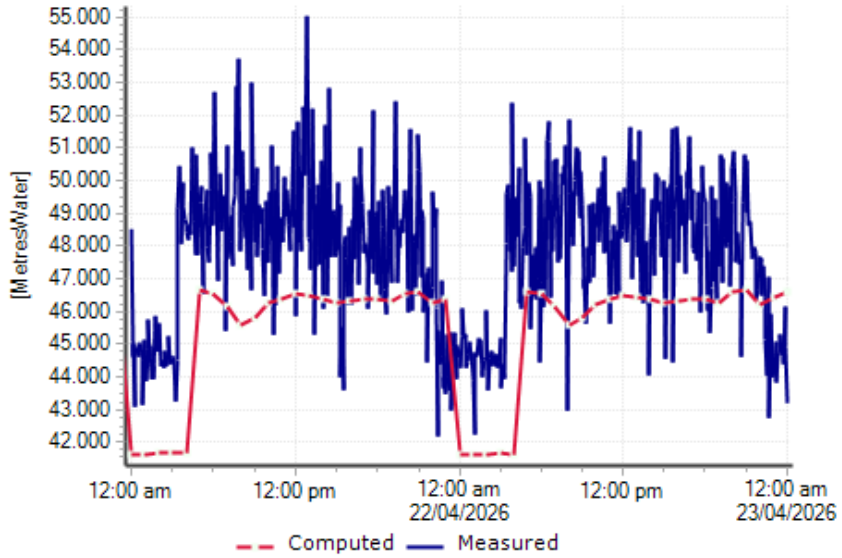


Figure 5.10. Validated Measurements: Station\_1, Pressure (mWC)

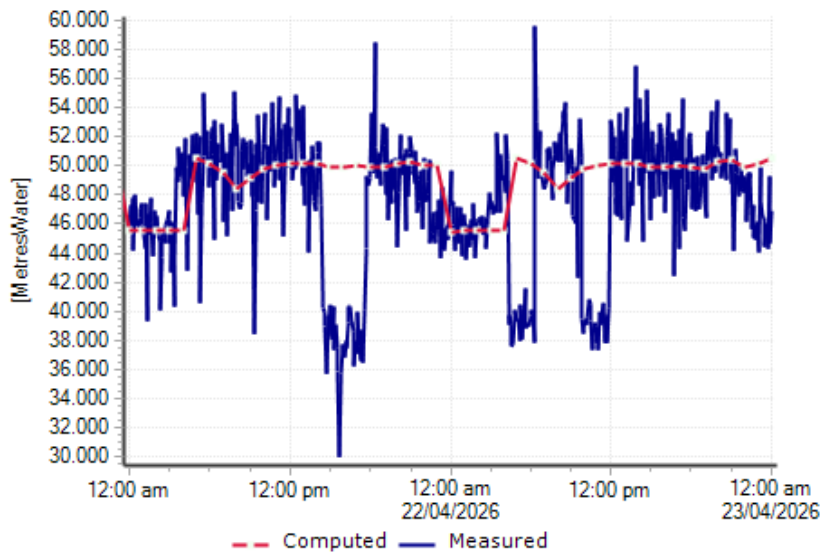


Figure 5.11. Validated Measurements: Station\_2, Pressure (mWC)

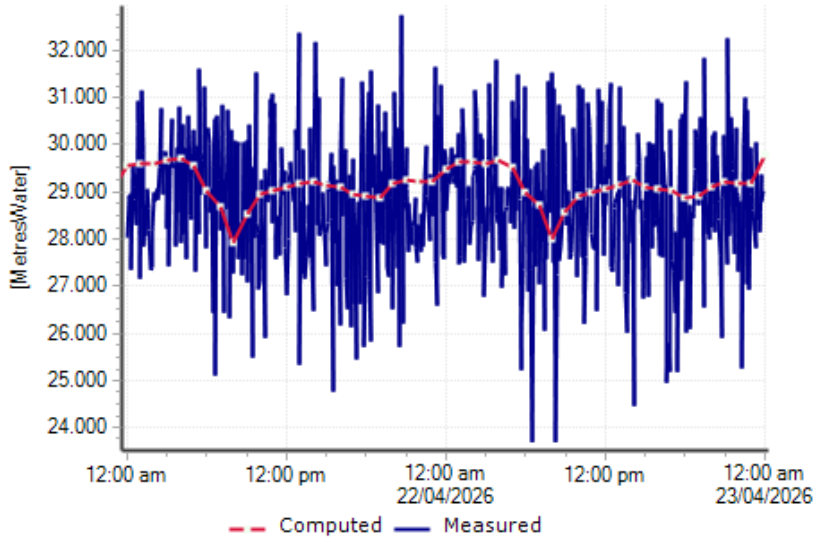


Figure 5.12. Validated Measurements: Station\_3, Pressure (mWC)



## 6. Scenarios and Analyses

### 6.1. Scenarios

After calibration and validation, the base model was used to represent the current operating conditions of Kirke Eskilstrup Waterworks during the study period. The base model describes the existing distribution system under normal demand and operational settings and provides the reference condition for evaluating the effects of leakage and high demand.

Two additional scenarios were developed from the calibrated base model. Scenario 1 represents the base model with leakage under normal demand conditions. In this scenario, leakage was added to the system while keeping the original calibrated model structure and operating conditions unchanged. This scenario was used to assess the effect of physical water losses on pressure distribution, flow patterns, pump energy use, and pump efficiency.

Scenario 2 represents the base model with leakage under high-demand conditions. This scenario used the same leakage condition as Scenario 1 but included an increase in residential demand to represent elevated seasonal demand. The purpose of this scenario was to evaluate how the distribution system responds when leakage occurs, together with higher water consumption.

The high-demand scenario was developed by applying a demand multiplier of 1.2 to the residential demand category. This multiplier was selected based on the seasonal demand factor reported in Miljøprojekt nr. 998, where summer consumption for detached and row houses was approximately 1.2 times higher than the average monthly demand (Miljøstyrelsen, 2005). Since the high-demand scenario represents summer consumption, the multiplier was applied only to residential users.

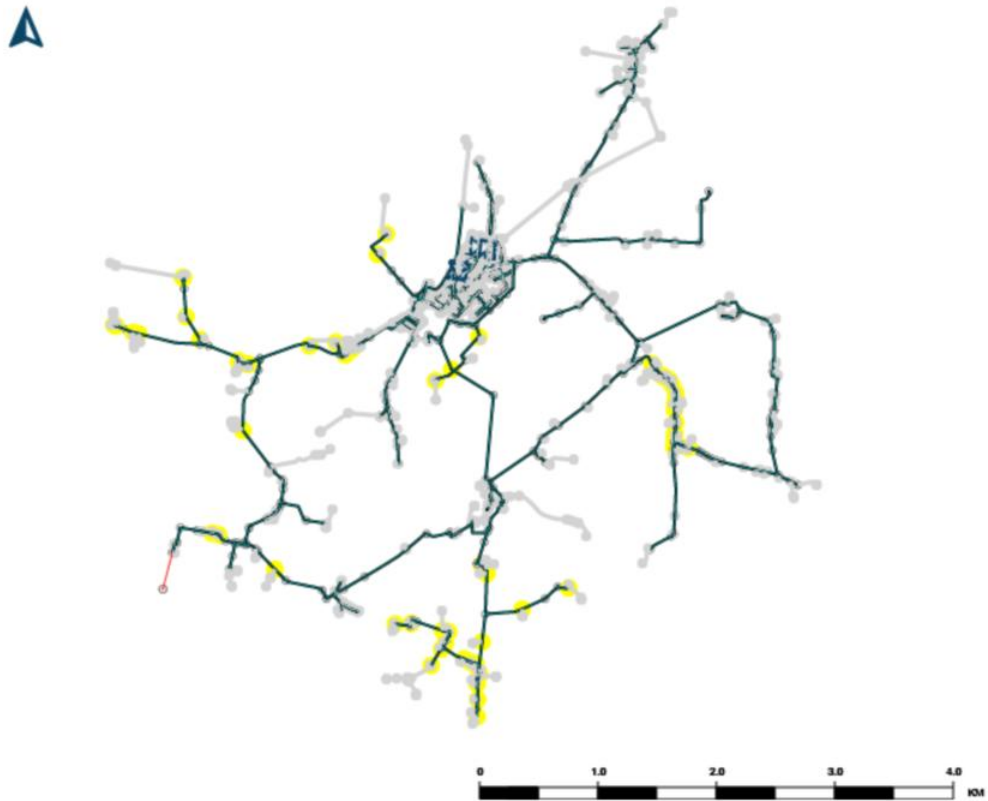
According to Miljøprojekt nr. 998, there is insufficient evidence of significant changes in summer consumption patterns for commercial and agricultural users. Therefore, commercial and agricultural demands were kept unchanged in the model. This assumption is considered reasonable because the network is mainly composed of residential consumers, who account for approximately 75% of the total annual water consumption. As a result, increasing residential demand is expected to have a noticeable effect on the overall water consumption and hydraulic response of the system.

Leakage was maintained in the model as additional nodal demand, allowing the combined effect of physical water loss and increased summer residential consumption to be assessed.

## **6.2. Leakage Modelling and Analysis**

There are different ways to represent leakage in a water distribution model. As Taghlabi et al. describe, leakage modelling can be done either by adding an additional node demand or by adding a leak valve (Taghlabi et al., 2020). This study employed the additional nodal demand as leakage. In this method, the leak flow is added directly at selected junctions. It is simpler to apply as it does not require calibration of emitter coefficients and is suitable when the objective is to evaluate the general impact of leakage on system performance, pump operation, and energy consumption (Chambon et al., 2023).

The leakage nodes were selected based on two conditions. First, the junctions with node pressure (maximum) greater than 43.5 mWC were selected, as higher pressure nodes are more vulnerable to leakage. This pressure threshold was chosen based on the base model's pressure distribution, in which pressures above 43.5 mWC were considered as the upper pressure range of the system, which will be detailed further in the results chapter. The second condition is that only junctions with existing demand allocation were considered, as the leakage was represented as additional nodal demand. In total, there were 72 leakage nodes that met the two conditions, highlighted in yellow in Figure 6.1.



*Figure 6.1. Leakage nodes in the distribution system*

Finally, a leakage scenario was developed by adding 5% leakage to the system, based on the leakage estimate provided by the water utility. The leakage was distributed to selected high-pressure nodes to assess how physical water losses may affect pressure distribution, pump operation, energy consumption, and operational cost under normal and high-demand conditions.

### **6.3. Cost Analysis**

The cost analysis was performed using the built-in cost analysis module in MIKE+ to estimate the operational electricity cost associated with pump operation under the simulated scenarios. The analysis was conducted for both normal demand and high-demand conditions to compare the pumping cost impacts of leakage under different system loading conditions.

The analysis focused only on electricity consumption for pumping and did not include other costs such as capital investment, pump maintenance, labour, pipe rehabilitation, or leakage repair. The electricity price used in the calculation was based on Energinet's 2025 annual report. Since Kirke Eskilstrup is located in Zealand, which belongs to the DK2 electricity price area, an average electricity price of 82.5 EUR/MWh, equivalent to 0.0825 EUR/kWh, was applied in the analysis (Energinet, 2026).

## **6.4. Stakeholder Mapping and Value Analysis**

This study utilizes Stakeholder Value Mapping as an approach for determining how stakeholder groups gain from complex systems, especially in research associated with sustainability. It gives a systematic approach to identify, classify, and assess value creation across multiple actors for better decision-making (Winans et al., 2021). In practice, stakeholder value mapping is often used in environmental and infrastructure planning to identify key actors, analyse their roles and influence, and improve coordination and governance results. Moreover, recent studies indicate a trend toward multi-dimensional value perceptions, wherein social, environmental, and economic values are taken into account concurrently across stakeholder groups (Freudenreich et al., 2020).

This chapter identifies and analyses the key stakeholders relevant to the study, focusing on their roles, interactions, the value they gain from the study results, and how the results create value across these actors.

### **6.4.1. Stakeholder identification**

The following key stakeholders were identified based on their roles, responsibilities, and influence within the water supply system and its regulatory and operational context.

**Kirke Eskilstrup Waterworks** operates as a cooperative water utility responsible for ensuring drinking water quality up to the property boundary of its Cooperative Members. Individual property owners (consumers) are responsible for any changes in water quality during installations and private service pipes, although the waterworks provides

technical support and assistance as needed. A shared governance system between the utility and its consumers, where the public distribution network is managed collectively while private infrastructures are owned individually (KE Vand, n.d.). The waterworks participates in the Holbæk Water Council, a coordination forum established to represent local water utilities within Holbæk Municipality and to facilitate collaboration on issues of common interest.

The **Consumers** represent the end users of the DWDS and are directly affected by water quality, supply reliability, pressure conditions, and service interruptions. Their water consumption patterns influence the system and therefore play an important role in the network's hydraulic performance and operational management.

The **Holbæk Water Council** serves as a collective negotiating body in which local utilities coordinate on joint technical, regulatory, and administrative tasks and engage with municipal and national authorities (Undløse Vandværk, n.d.).

The **Municipality of Holbaek** is responsible for ensuring safe drinking water through collaboration with waterworks, landowners, businesses, and other authorities, and by administering relevant legislation. Municipalities in Denmark are responsible for planning, environmental engagement, and public services within their jurisdiction. The municipality prepares water supply plans, approves waterworks, and ensures compliance with national laws (Holbæk Kommune, n.d.).

The **Danish Waterworks Association** is a national organization representing Danish water utilities and waterworks that provides technical knowledge, training, advocacy, and policy engagement for water supply organizations, with an emphasis on groundwater protection, the green transition, digitalization, and consumer ownership of water resources. They also participate in policy consultations and provide sector guidance on regulatory frameworks and waterworks governance that bridge local utilities and national regulators (Danske Vandværker, n.d.).

The **Danish Environmental Protection Agency** is a national agency under the Ministry of Environment responsible for implementing environmental policies related to nature, water, and pollution control. In the context of drinking water systems, the agency has a regulatory and

advisory role in developing legislation, setting water quality standards, and providing guidance on groundwater protection and monitoring (Danish Environmental Protection Agency, 2024).

**Ramboll** is a Danish multinational engineering, architecture, and consultancy company founded in Copenhagen, Denmark in 1945, delivering multidisciplinary services across sectors including water, environment and health, energy, transport, and buildings (Ramboll, n.d.). Within the water sector, Ramboll provides engineering design and advisory, modelling, and planning services across the entire water cycle, including water resources management, drinking water infrastructure, wastewater treatment, and climate resilience planning. The company supports water utilities and municipalities in assessing risks, optimising water systems, and planning infrastructure investments, particularly in the context of climate change and regulatory requirements such as the European Water Framework Directive (Ramboll, n.d.).

The **UN-Water** is an inter-agency coordination mechanism that aligns the work across the UN members and partners dedicated to water and sanitation problems. UN-Water supports countries by informing policy processes, monitoring progress toward SDG 6, and building knowledge to inspire action (UN-Water, 2024). Denmark actively supports SDG 6 through national water policies and the Danish water sector, where organizations such as DANVA promote sustainable water management, operational efficiency, and reduction of water losses in DWS (DANVA, 2025).

The **European Union**, particularly the European Commission through its environmental policy framework, is responsible for developing and implementing EU legislation related to water resource protection and sustainable water management. The EU Water Framework Directive (WFD) (Directive 2000/60/EC) establishes a comprehensive framework for water policy across member states, requiring good ecological and chemical status of water bodies and integrated water management (European Parliament & Council of the European Union, 2000).

A summary of the identified stakeholders, including their respective scales and roles within the DWDS, is presented in Table 6.1.

Table 6.1. Summary of Stakeholders, Scale, and Roles

SCALE	STAKEHOLDER	ROLE
Local	Kirke Eskilstrup Waterworks	Utility operator
Local	Cooperative members (Consumers)	Private households, agricultural users, and commercial owners
Local	Holbæk Water Council	Coordination platform
Local	Holbæk Municipality	Supervisory authority at the regional level
National	Danish Waterworks Association	Local water utilities in Denmark
National	Ramboll	Engineering consultancy
National	DANVA	Non-profit Organization (Water Sector)
National	Danish Environmental Protection Agency	Supervisory authority at the national level
International	European Union (European Commission)	Regulatory and policy framework
International	UN Water	Global policy and development agenda

### 6.4.2. Stakeholder Value Analysis

In this study, the distribution of benefits from the hydraulic model optimization varies across stakeholders and is assessed using five value categories: Operational, Economic, Knowledge, Regulatory, and Environmental value. These categories provide a structured framework to capture both direct and indirect impacts of the results of the study.

*Operational* value refers to improvements in system performance, such as pressure stability and leakage reduction. *Economic* value reflects cost savings and increased efficiency in system operation. *Knowledge* value reflects enhanced system understanding, data availability, and decision-making

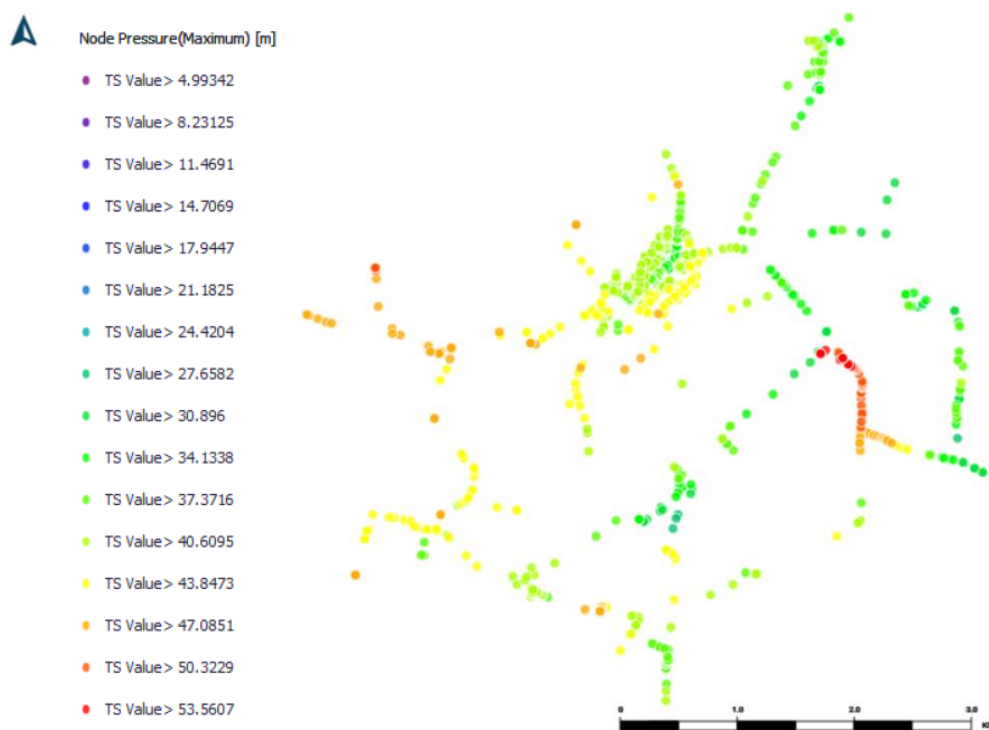
support. *Regulatory* value refers to improved compliance, monitoring, and alignment with policy requirements, whereas *Environmental* value captures benefits related to reduced water losses and energy consumption, contributing to sustainability goals.

The level of benefit (high, medium, or low) is determined based on the stakeholder's degree of direct interaction with the hydraulic model outputs and the extent to which each stakeholder can translate these tangible operational, economic, or decision-making improvements.

## 7. Results

### 7.1. Base Model Functional Analysis

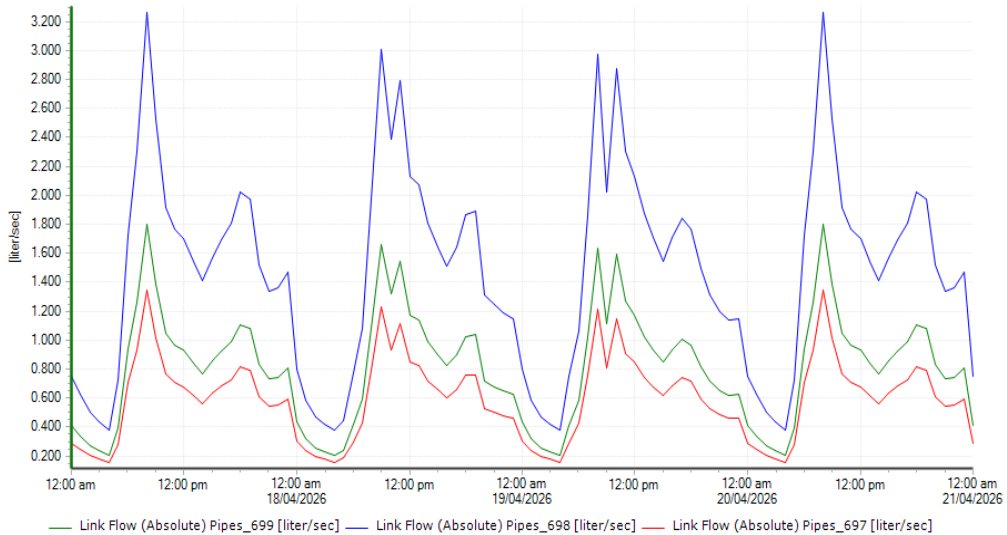
This focuses on the functional analysis of the existing system performance, with emphasis on how the network operates under current demand patterns, pump settings, and hydraulic conditions. The results of this scenario provide a reference case for further analysis before introducing leakage and high-demand conditions.



*Figure 7.1. Base Model Node Pressure (m) (Maximum)*

The base model results show a clear variation in nodal pressure across the distribution network, as depicted in Figure 7.1. Based on the pressure distribution, most nodes are concentrated around the green to yellow-green classes, corresponding to approximately 34–41 mWC. This indicates that the average system pressure is visually estimated to be around 38–40 mWC. In this study, nodes with pressures above 43.5 mWC were classified as high-pressure nodes because they represent the upper pressure range of the system.

These nodes were selected as potential leakage-sensitive areas in the following scenario, as higher pressure can increase leakage flow and pipe stress.



*Figure 7.2. Flow (l/s) (Absolute) through the main outgoing pipes*

The daily flow in the three main pipes going out from the waterworks shows a clear repeated pattern in Figure 7.2. Flow is lowest during low-demand periods, around 0.15-0.7 l/s, and increases sharply during high-demand periods. The highest flow occurs in Pipe\_698, which reaches a peak value of 3.0 l/s. Pipe\_699 carries the second-highest flow, with peaks around 1.6-1.8 l/s, while Pipe\_697 carries a flow with a peak of 1.2-1.3 l/s. The three pipes follow a similar timing pattern and respond to the system’s demand cycle and pump operation, although outflow is not evenly distributed across the three outgoing pipes.

The pump energy consumption and efficiency results for the waterworks are presented in Figures 7.3 and 7.4. The energy consumption for Pump\_1 shows a repeated daily pattern, ranging from around 2.1 kW to 3.8 kW. The pump efficiency follows a similar pattern, with peak values reaching 55-56%. It shows that Pump\_1 operates continuously during the simulation and changes according to system hydraulic conditions.

In contrast, Pump\_2 only operates during the initial part of the simulation. Its energy consumption spikes briefly, together with the efficiency curve, as higher energy consumption generally corresponds to higher pump efficiency.

After the initial period, Pump\_2 becomes inactive for the rest of the simulation. It shows that Pump\_2 does not contribute and behaves as a standby or backup pump.

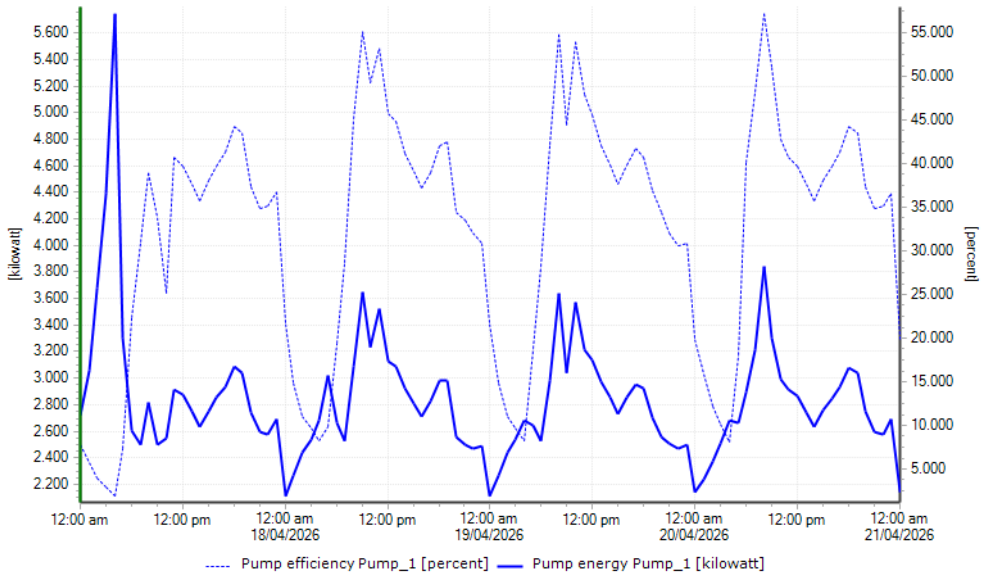


Figure 7.3. Pump\_1, Pump Energy vs Pump Efficiency

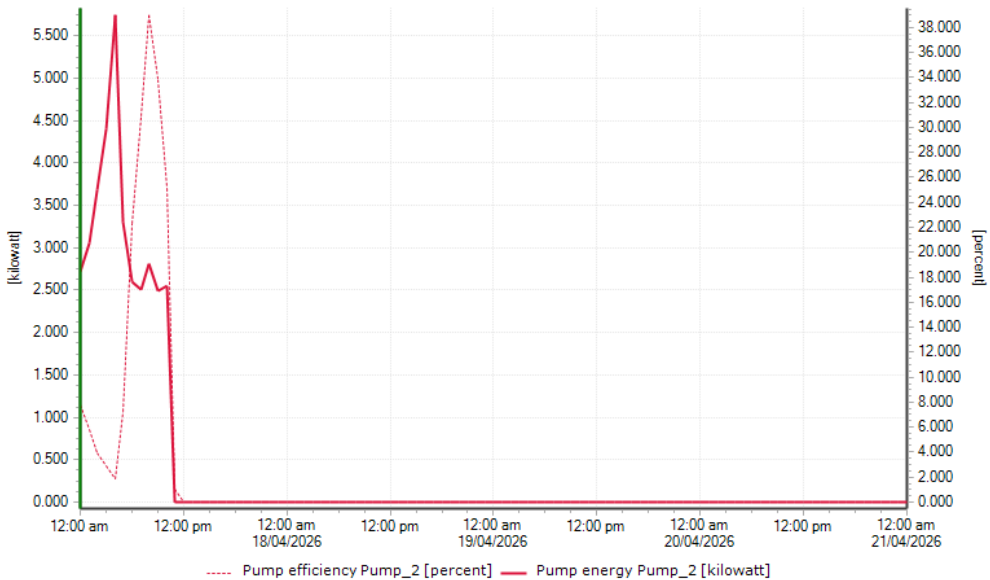


Figure 7.4. Pump\_2, Pump Energy vs Pump Efficiency

Based on this, Pump\_1 was identified as the primary operating pump and was considered sufficient to supply the system under normal operating conditions. Pump\_2 was disabled in the following simulations, and the leakage and energy analyses were carried out with Pump\_1 as the only active pump.

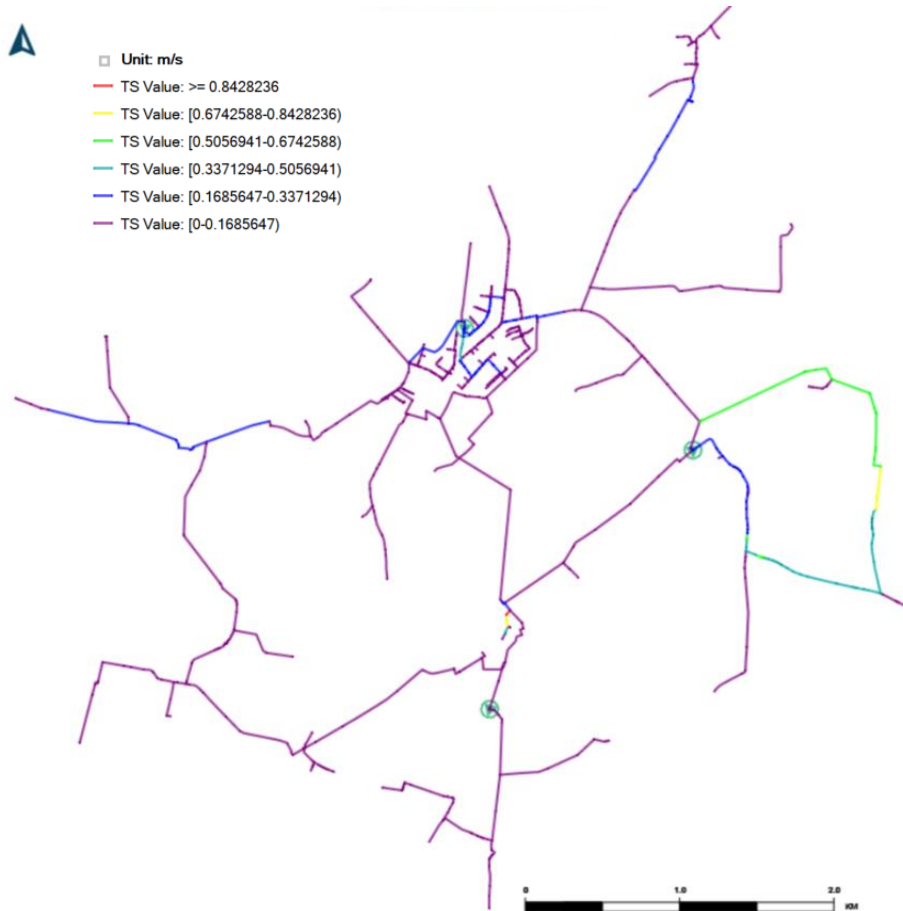


Figure 7.5. Velocity (m/s) through links (maximum)

The link velocity map shown in Figure 7.5 shows that most pipes in the base model operate at low velocities around 0.17 m/s. Some pipes increase to 0.34 m/s, showing higher movement during the high-demand period. The highest velocities reached 0.51-0.84 m/s around a loop concentrated in the Eastern part of the network, the area supplied by Booster\_2.

The maximum link flow map presented in Figure 7.6 shows that higher flows are concentrated around the waterworks and along the main transmission routes, while most peripheral and tree branches carry relatively lower flows.

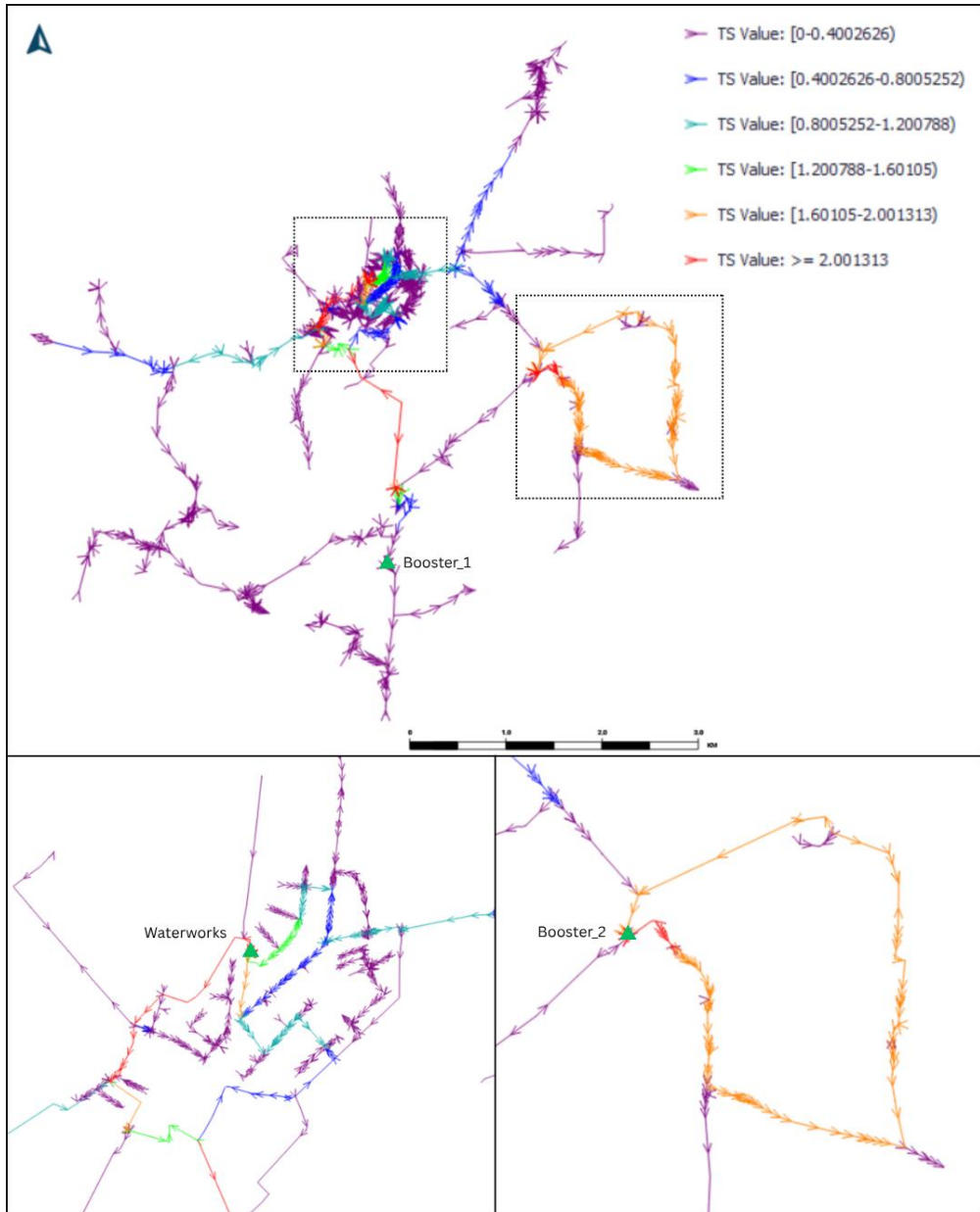
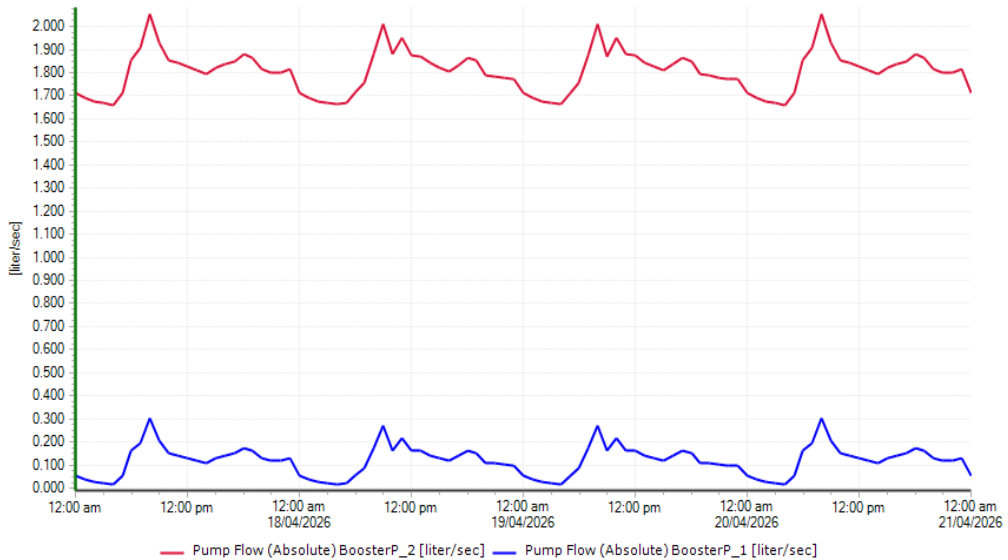


Figure 7.6. Flow (l/s) through pipes (maximum)

The locations of the booster pumps are marked with a green triangle. Booster\_1 appears to supply a dead-end branch, where flow is a single path and does not circulate back through the network. In contrast, in the lower-right zoomed panel, it can be seen that Booster\_2 is positioned at the point where the flow enters a looped zone. The pipes inside the loop have a flow of about 1.60-2.00 l/s. The arrows show that water moves along multiple connected paths where the flow is circulating.



*Figure 7.7. Booster Pumps Flow (l/s) (Absolute)*

The flow distribution observed is further supported by the booster pump flow results, as illustrated in Figure 7.7. Booster\_2 has a relatively higher flow of about 1.65-2.05 l/s, while Booster\_1 operates at much lower flows between 0.05-0.3 l/s.

## 7.2. Scenario 1: Base model with Leakage under normal demand conditions

In scenario 1, the base model was simulated with 5% leakage, and Pump\_2 was disabled. Figure 7.8 shows the nodal pressure distribution for the additional leakage under normal demand conditions. It is generally similar to the base model, where most nodes remain within the same pressure range.

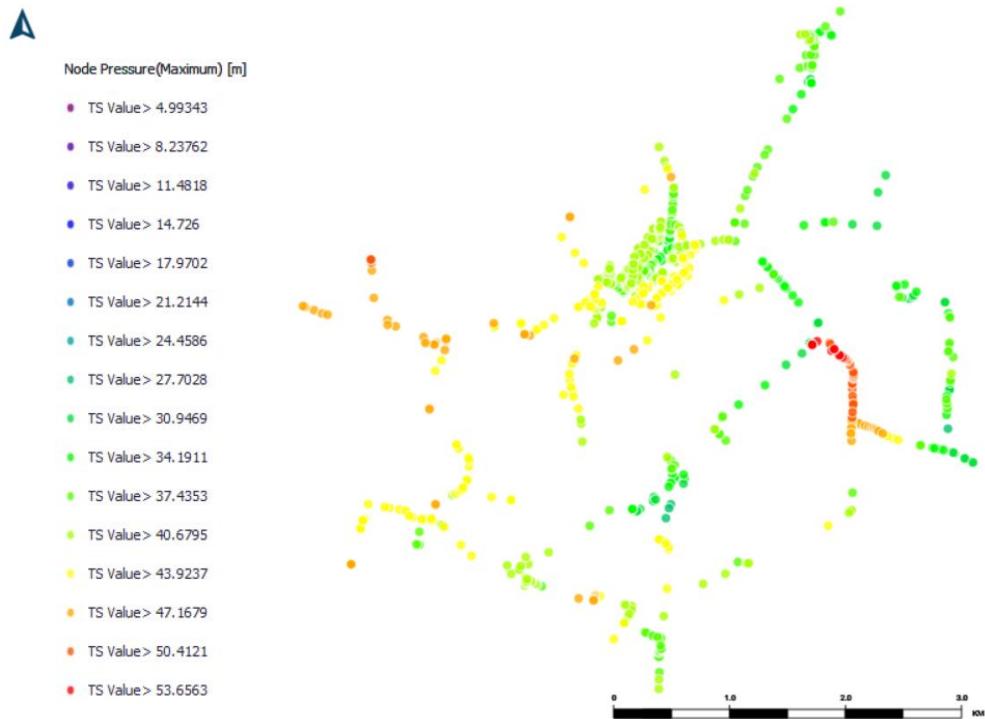
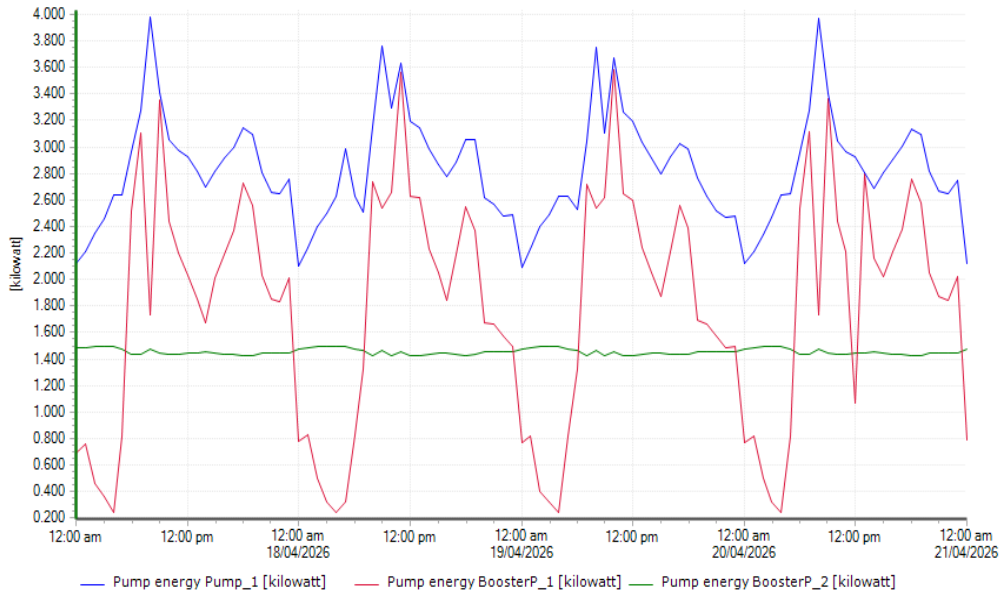


Figure 7.8. Node Pressure (m) (Maximum) Scenario 1



*Figure 7.9. Pump Energy (kW) for Scenario 1*

The results from Figure 7.9 show that Pump\_1 was able to supply the system after implementing additional leakage. The pump power is around 2.1 kW during low-demand periods and 4.0 kW during high-demand periods. Compared with the base model, the pump behaviour in this scenario is more stable, and the initial spikes observed at the beginning of the simulation are no longer present. The fluctuations observed in scenario 1 were likely caused by the initial operation of Pump\_2 or by the interaction between the two pumps.

The booster pumps show different energy patterns under the leakage scenario. Booster\_1 has a highly variable power consumption, with values ranging from around 0.2 kW during low-demand periods to more than 3.0 kW during peak-demand periods. In contrast, Booster\_2 remains relatively stable at around 1.4–1.5 kW throughout the simulation. This stable behaviour may be related to the location of Booster\_2 at the entrance of a looped section of the network. Overall, the leakage scenario increased the hydraulic load on the pumping system.

The pump efficiency results shown in Figure 7.10 support the interpretation of the pump energy patterns. Pump\_1 shows the highest efficiency among the pumps, with efficiency increasing during high-demand periods and reaching approximately 56–58%. Booster\_2 shows a relatively stable efficiency, mostly around 27–33%. In contrast, Booster\_1 has very low efficiency, mostly close to 1–3%, despite showing large fluctuations in energy consumption.

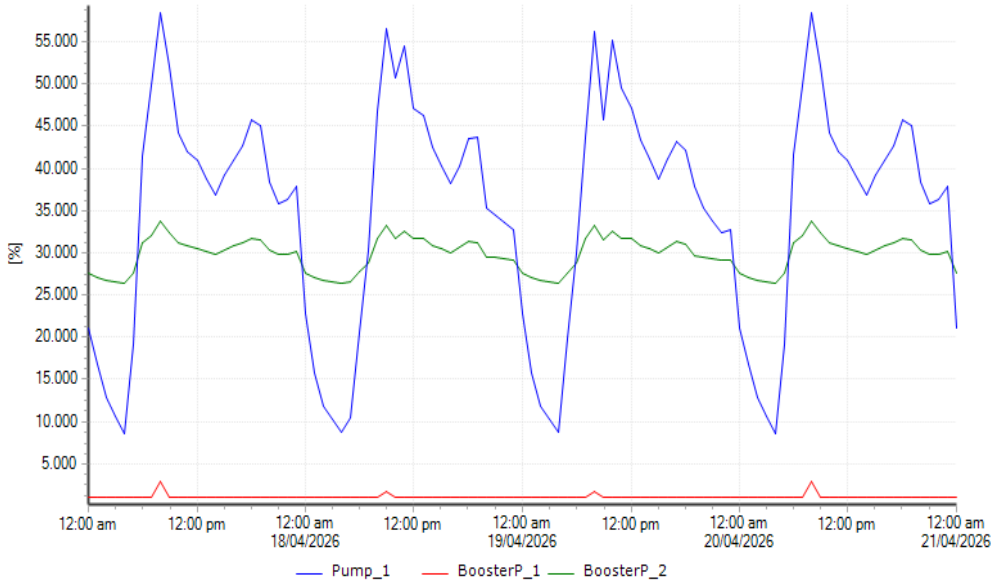


Figure 7.10. Pump Efficiency (%) for Scenario 1

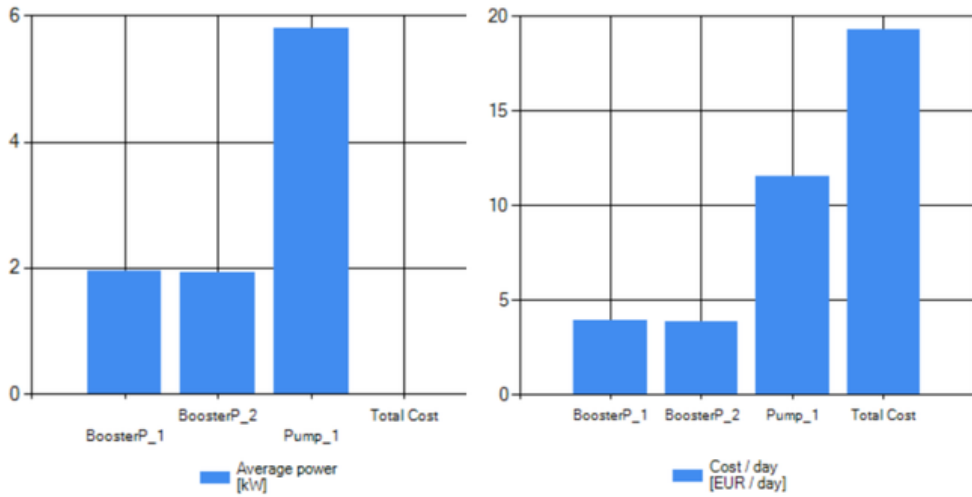


Figure 7.11. Average Power (kW) and Daily Cost (EUR/day) for Scenario 1

The average power results in Figure 7.11 show that Pump<sub>1</sub> had the highest average power demand among the pumps, while the booster pumps have almost the same average power demand. The cost analysis results for the leakage scenario under normal demand conditions show a total estimated

pumping cost of approximately 19 EUR/day. Pump\_1 accounted for the largest share of the cost, with approximately 11.5 EUR/day, while Booster\_1 and Booster\_2 contributed around 4 EUR/day.

### 7.3. Scenario 2: Base model with Leakage under high demand conditions

Figure 7.12 shows the nodal pressure distribution for the additional leakage and high-demand condition. Compared with scenario 1, more high-pressure nodes, shown in red, are observed, particularly near the booster-supplied areas.

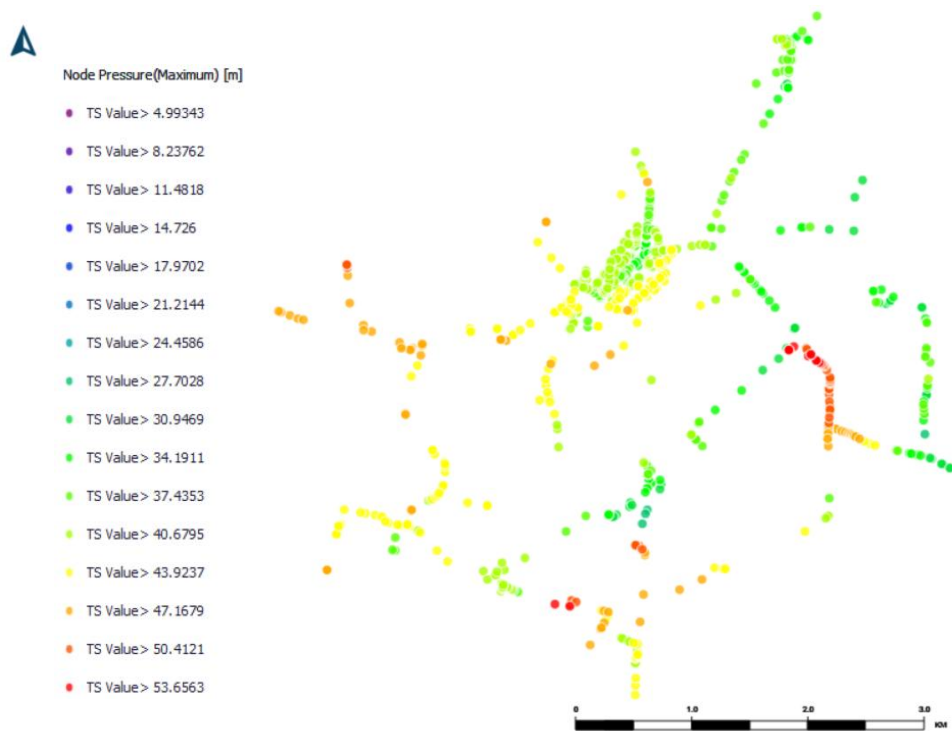


Figure 7.12. Node Pressure (m) (Maximum) Scenario 2

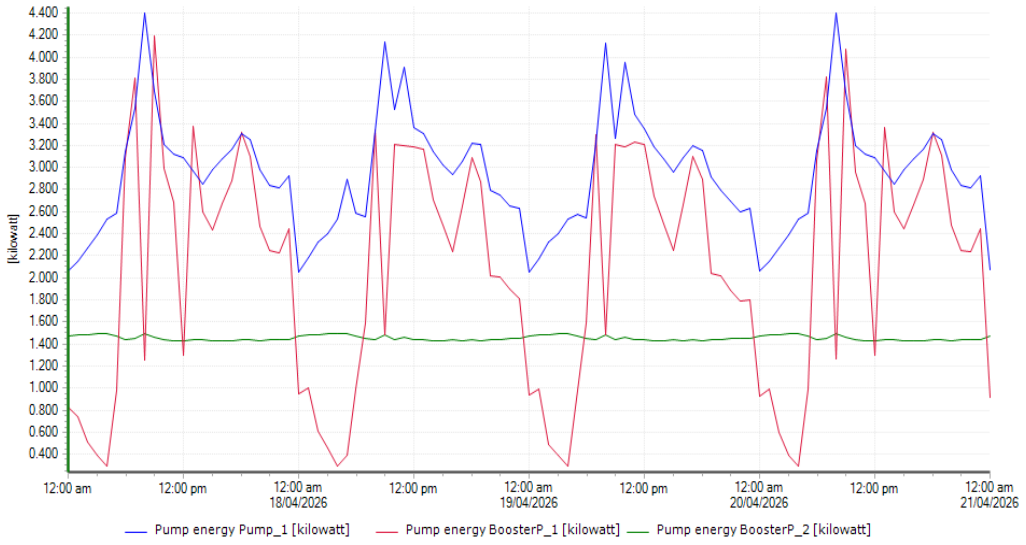


Figure 7.13. Pump Energy (kW) for Scenario 2

The pump energy consumption under the high-demand summer leakage scenario is shown in Figure 7.13. The power consumption in Pump\_1 ranged from approximately 2.0 kW during low-demand periods to about 4.5–4.6 kW during high-demand periods. Booster\_1 showed a peak ranging from 3.4-4.2 kW. Booster\_2 showed nearly constant power consumption of approximately 1.4–1.5 kW throughout the simulation.

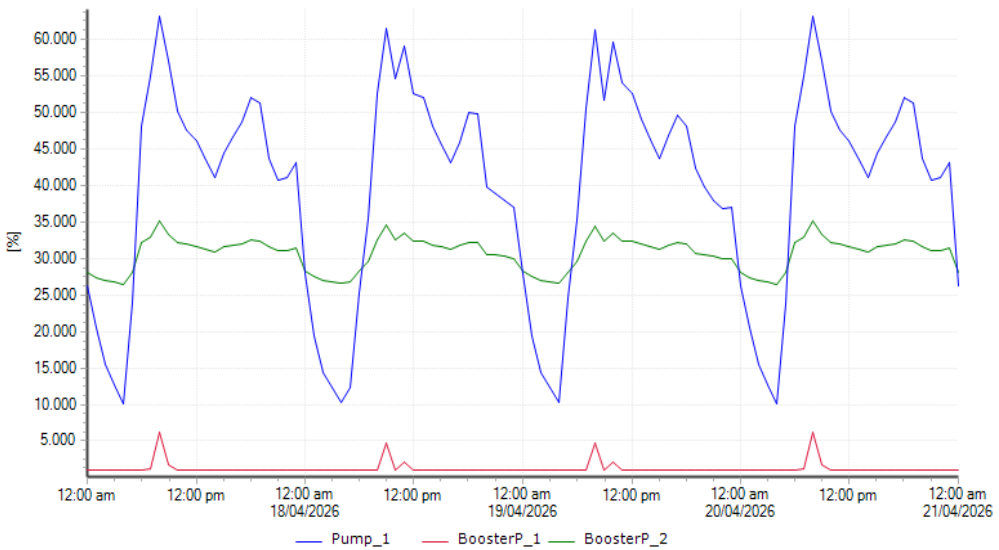


Figure 7.14. Pump Efficiency (%) for Scenario 2

The pump efficiency results are presented in Figure 7.14. Pump\_1 had a higher value compared to scenario 1, with values increasing during high-demand periods and reaching approximately 60–63%. This indicates that the higher hydraulic load under summer demand conditions increased Pump\_1's operating efficiency range. Booster\_2 showed relatively stable efficiency, mostly between approximately 27% and 35%, which is consistent with its stable energy consumption. In contrast, Booster\_1 operated at very low efficiency, generally close to 1–6%, despite large fluctuations in its power consumption.

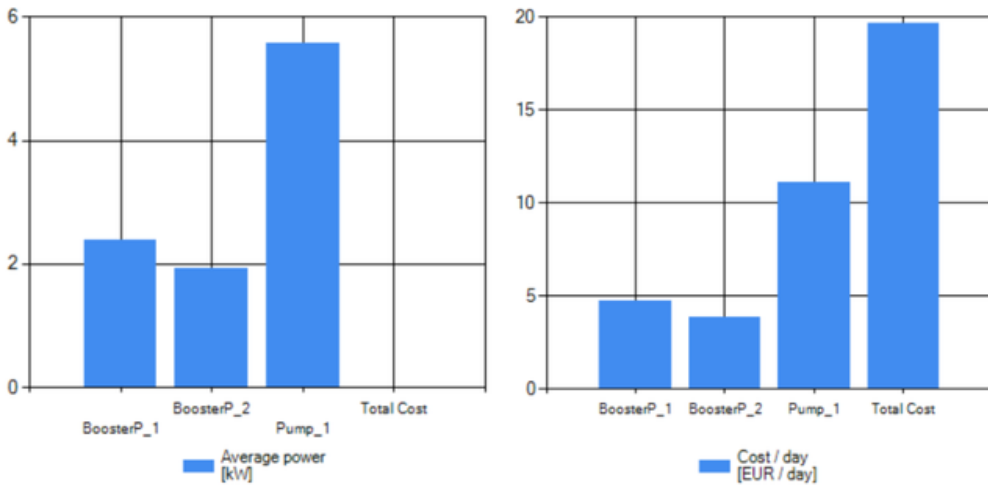


Figure 7.15. Average Power (kW) and Daily Cost (EUR/day) for Scenario 2

The average power results in Figure 7.15 show that Pump\_1 remained the dominant contributor to average power demand under high-demand conditions, while the booster pumps showed smaller changes compared with Scenario 1.

Under the high-demand summer leakage scenario, the total estimated pumping cost increased slightly to 20 EUR/day. The increase is mainly caused by Booster\_1, which increased to 5 EUR/day, while Pump\_1 and Booster\_2 remained about 11 EUR/day and 4 EUR/day, respectively, as in scenario 1.

## 7.4. Stakeholder Analysis

The analysis shows that benefits are unevenly distributed across stakeholder groups, with the most direct impacts occurring at the local level. The Kirke Eskilstrup Waterworks and its cooperative members (consumers) derive the highest operational and economic value due to their direct interaction with the system.

Stakeholders such as the Holbæk Water Council, Holbæk Municipality, local water utilities in Denmark, and Ramboll have moderate benefits, primarily from knowledge and regulatory value that supports planning and coordination.

At the national and international levels, stakeholders, including the Danish Environmental Protection Agency and DANVA, as well as broader entities like the European Commission and the UN-Water, benefit more indirectly through contributions to policy development, benchmarking, and sustainability objectives, which may be translated into improved planning initiatives, performance comparison between utilities, and the development of more sustainable water management practices.

*Table 7.1. Stakeholder Value Mapping*

<b>Stakeholder</b>	<b>Benefit</b>	<b>Type of Value</b>	<b>Benefit Level</b>
Kirke Eskilstrup Waterworks	Improved pressure control, leakage reduction, and optimized pump operation	Operational, Economic, Knowledge	High
Consumers (Households, Farms, Businesses)	More stable supply, improved system reliability, and potential tariff stability	Economic, Operational	High
Holbæk Water Council	Potential improvement in coordination through application of hydraulic model	Knowledge, Regulatory	Medium

Holbæk Municipality	Better decision support for infrastructure planning and compliance	Regulatory, Knowledge	Medium
Local Water Utilities in Denmark	Transferable modelling approach, benchmarking opportunities, and optimization insights	Knowledge	Medium
Ramboll	Demonstration of modelling capability and improved consultancy outcomes	Knowledge, Economic	Medium
DANVA	Case-based insights to support benchmarking, performance evaluation, and environmental performance	Knowledge, Environmental	Low
Danish Environmental Protection Agency	Improved basis for monitoring compliance and environmental performance	Knowledge, Environmental	Low
UN Water	Transferable modelling approach that may support and contribute to SDG 6 through improved water system efficiency and sustainable water management practices	Environmental	Low
European Union (European Commission)	Contribution to policy objectives and sustainable water management under the Water Framework Directive	Regulatory, Environmental	Low

## 8. Discussion

### 8.1. System performance

The scenario results show that the system is hydraulically capable of maintaining service under the simulated leakage and high-demand conditions. The leakage scenario did not cause major hydraulic changes under normal conditions. However, when leakage and high demand conditions were combined, more high-pressure nodes were observed near the booster-supplied areas. This indicates that some parts of the network may remain exposed to elevated pressure, which is relevant as high-pressure areas are more vulnerable to leakage.

The velocity results also indicate that the network is not overloaded, which suggests that the system has sufficient capacity under the two simulated conditions. Although the generally low velocities in most of the pipes may indicate oversized pipes relative to low demand, this could be relevant for water age and water quality considerations.

The pump results show that Pump\_1 is the main supply pump and was able to supply the system after leakage and high-demand conditions were implemented. Pump\_1 efficiency increased as the hydraulic load increased during the high-demand conditions. This suggests that the pump operates closer to its efficient range when demand is higher. However, part of the additional pumped water represents leakage rather than useful consumption.

The booster pumps showed different operational behaviour. Booster\_1 followed the general pump operation pattern, and the energy consumption increased during high-demand conditions. However, despite the energy fluctuations, Booster\_1 operated at very low efficiency. This is likely because the flow through Booster\_1 remained low; the pump consumed energy but produced limited output. This suggests that Booster\_1 may be operating outside its optimal efficiency range, possibly due to low local water demand, pump oversizing, or pump control settings that do not match the branch it supplies. In contrast, Booster\_2 behaved more steadily, with an almost flat energy consumption pattern and stable efficiency. Unlike Booster\_1, it did not closely follow the pump-operation pattern. This may be related to its location in the entrance of a looped section of the network, where flow may circulate

through several connected paths. This indicates that the network layout has an important influence on the pump performance.

The cost analysis shows the economic effect of the simulated changes related to pumping use. With leakage under normal conditions, the estimated pumping cost was 19 EUR/day, while 20 EUR/day under high-demand conditions. Although the increase is relatively small, the pumps should be operated as efficiently as possible because leakage represents a continuous and avoidable cost. The analysis only considered electricity use for pumping; therefore, the actual economic impact may be higher if maintenance, labour, pipe rehabilitation, and capital costs are included.

## **8.2. Limitations and Uncertainties**

The results of this study should be interpreted in relation to the assumptions and simplifications applied during model development. First, some network parameters, including pipe diameter, pipe material, and roughness, were interpolated and estimated. Although these assumptions were necessary to complete the hydraulic model, they introduce uncertainty into the simulated pressure, flow, and energy results.

The water demand was based on annual consumption data, which were disaggregated into daily demand and assigned to the nearest active distribution nodes. This simplification may not fully represent the spatial distribution of consumption, local demand variations, and short-term peak demand.

Most of the collected field-measured data consisted of pressure measurements, while flow measurements within the distribution network were unavailable. As a result, the calibration and validation process relied primarily on pressure comparisons, which limits the ability to fully evaluate the hydraulic behavior and flow distribution throughout the system.

Leakage was represented as an additional nodal demand at selected high-pressure nodes. This approach is suitable for evaluating the general effect of leakage on pump energy and pressure distribution, but it does not represent pressure-dependent leakage behavior. In reality, leakage flow changes with pressure, and the actual leakage may vary over time and between locations.

The high-demand scenario was developed by applying a multiplier to residential demand only, while commercial and agricultural demand remained unchanged due to limited seasonal data. Therefore, the high-demand scenario

should be interpreted as simplified demand conditions due to summer activities, such as watering of plants, more frequent showering, use of pools, etc., rather than complete seasonal demand behavior.

Finally, the storage tanks were represented as fixed-level reservoirs with constant HGL. This means that tank filling and emptying, available storage and capacity, and possible pump scheduling based on storage levels were not evaluated. Due to this, the model can assess network hydraulic response and pump energy under the simulated conditions, but it cannot fully evaluate operational strategies that depend on active tank storage. This is important because tank operation could highly influence pump scheduling and energy-cost optimization.

### **8.3. Suggestions for optimization**

For a small water utility such as Kirke Eskilstrup, operational costs are strongly linked to pumping energy. Although the simulated increase in cost between the leakage and high-demand scenarios was relatively small, pumping represents a continuous operational cost that can accumulate over time. Therefore, optimization suggestions are focused on reducing unnecessary pumping, improving pump efficiency, and limiting avoidable water losses.

One possible optimization measure is to investigate whether the storage tank can be used more actively in pump scheduling. If the tanks have sufficient storage capacity, pumping could be scheduled during periods with lower electricity prices, while pumping during peak-price periods could be reduced. This would require further analysis of tank levels, storage volumes, and electricity price patterns, which were outside the scope of the present model because the tanks were modeled as fixed-level reservoirs.

Neither of the booster pumps is operating within its optimal efficiency range and should be investigated further. Reviewing the booster pump settings, local demand, and pressure setpoints could reduce unnecessary energy costs. The looped area near Booster\_2 should also be investigated, and possible measures such as checking the valve configuration, adding a check valve, or closing selected valves could be done without reducing the service pressure or system reliability.

High-pressure nodes should also be prioritized for leakage monitoring. Although the 5% leakage level provided by the water utility is below the 15%

threshold stated in the EU Drinking Water Directive, high-pressure areas remain important due to the risk of leakage, which could increase operational cost.

#### **8.4. Stakeholder relevance of the results**

The relevance of the modelling results for the stakeholders depends not only on the hydraulic performance assessment itself, but also on the reliability, applicability, and operational usability of the model outputs. While the stakeholder value mapping identified several direct and indirect benefits, the practical uptake of the results could be further improved. For example, the inclusion of additional field measurements, more detailed consumer demand data, and improved information on component characteristics could increase model accuracy, stakeholder confidence in the results, and the usefulness of the model for operational planning and long-term decision-making.

These improvements could strengthen the relevance of the model results not only for the water utility and its consumers, but also for broader stakeholders concerned with sustainable and efficient water management.

## 9. Conclusion

This study developed and applied a calibrated hydraulic model of the Kirke Eskilstrup water distribution network to evaluate system performance under the simulated scenarios. Although this study focused primarily on leakage and operational cost assessment, the developed hydraulic model can also support further analyses, such as water quality assessment, fire flow analysis, and future demand growth evaluation.

The system is hydraulically capable of maintaining service under the simulated demand conditions. The 5% leakage scenario under normal conditions did not cause major changes in the pressure distribution. However, when leakage was combined with high-demand conditions, more high-pressure nodes were observed, indicating that these locations should be prioritized for leakage monitoring.

Pump\_1 was identified as the main supply pump and was able to supply the system after Pump\_2 was disabled. Its efficiency increased under higher hydraulic load, but part of the additional pumped water represented leakage rather than useful consumption. The booster pumps showed different behavior: Booster\_1 operated at very low efficiency despite consuming energy, while Booster\_2 showed stable operation, likely influenced by its location near a looped section of the network. These results indicate that the booster pump operation and the looped network area should be investigated further.

The cost analysis showed a slight increase under normal and high-demand conditions. Although the increase is small, pumping is a continuous operational cost for a small water utility, and leakage-related energy use can accumulate over time. Therefore, future optimization should focus on improving pump operation, investigating active tank use for pump scheduling, reviewing booster pump settings, and monitoring high-pressure areas for leakage.

Overall, the hydraulic model provides a useful decision-support tool for identifying operational improvements and supporting future planning for the waterworks. The model should therefore be used as a starting point for further operational testing, especially for pump scheduling, booster pump control, and targeted leakage management.



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