Master Thesis
TVVR 24/5005

Operation of waterworks to minimise energy consumption under large seasonal variations in demand.

An application to Djurs Vand Erhverv A/S in Denmark

Astrid Teresa Carolina Cifuentes Meza

Operation of waterworks to minimize energy consumption under large seasonal variations in demand

An application to Djurs Vand Erhverv waterworks in Denmark

By:
Astrid Teresa Carolina Cifuentes Meza

Master Thesis

Division of Water Resources Engineering
Department of Water Resources Engineering VVRM01
Faculty of Engineering, LTH
Lund University
Box 118
221 00 Lund, Sweden

Water Resources Engineering
TVVR-24/5005
ISSN 1101-9824

Lund 2024
www.tvrl.lth.se

Master Thesis
Division of Water Resources Engineering
Department of Water Resources Engineering
Lund University

English title:	Operation of waterworks to minimise energy consumption under large seasonal variations in demand. An application to Djurs Vand Erhverv A/S in Denmark
Author:	Astrid Teresa Carolina Cifuentes Meza
Main Supervisor:	Magnus Larson
Co-Supervisor:	Jing Li
Co-Supervisor:	Wei Han
Co-Supervisor:	Carl Stagne
Examiner:	Kenneth M. Persson
Language:	English
Year:	2024
Keywords:	Drinking water supply, optimization, modelling

Acknowledgements

This thesis was proposed by Rambøll Denmark under the guidance and supervision of Wei Han, Lars Schindhelm and Carl Stagne. I would like to acknowledge their invaluable contributions to this work. Their comments, suggestions, and support have helped make this project possible through all the different stages.

I am immensely grateful to Magnus Larson, the main supervisor of this thesis, for all the guidance and support provided throughout this study. He has shared his knowledge and extensive experience in this investigation.

I would like to express my gratitude to my co-supervisor, Jing Li, for her suggestions and feedback and for always having a good disposition throughout this study.

I am grateful to Djurs Vand water utility director Tonny Sædam and also Jan True for their approval to use their data and provide all the information requested for this project.

Furthermore, this thesis would not have been possible without the student license provided and all the guidance material from DHI, the developer of the MIKE+ software.

I would also like to thank my mom and dad for their invaluable support throughout the period. Being them is my reason for always seeking to improve myself.

To my life partner for all his invaluable support throughout this period.

And last but not least, this publication has been produced during my scholarship period at Lund University, funded by the Swedish Institute.

Abstract

The intricate nature of water distribution networks and the challenge of managing seasonal water consumption variation pose a significant hurdle for water utilities striving for low energy consumption. The performance of pumps, which are the backbone of these networks, directly influences the energy required for distributing drinking water. Such conditions are modelled using MIKE+ for the water distribution network of Ebeltoft, Denmark. The waterworks Egedal in the study area provided data regarding pipes, components, and water consumption, among other databases, as input data for the model. In addition, pressure sensors were installed in 5 locations along Ebeltoft for the model calibration and validation stage, and data was downloaded from SCADA. The model calibrated and validated was used as input data to model the 10 % leakage in the pipes. After this, low and high-demand scenarios were simulated to assess the pump's energy consumption. The pump efficiencies for Zone 2 and Zone 3 were too low compared to Zone 1. Overall, the high-demand scenario had pumps working at increased efficiencies (6 and 7 %) compared to the low season. It was concluded that pumps were overcapacity for Zones 2 and 3. An alternative proposed is to install a pump with lower capacity, at least during the night hours.

Contents

1 Introduction

1.1 Background

Drinking water distribution networks are complex systems governed by various components, such as pipes, valves, and pumps, among other internal factors. However, factors external to the network, such as the topography of the place, play a primary role in providing or subtracting energy from the system. Nevertheless, pumps are usually the primary sources of energy injection into the system and the main sources of energy consumption. Because energy consumption is closely related to demand, areas strongly influenced by tourism are typically susceptible to seasonal fluctuations in population and demand variations during the year. In the summer, these areas become more popular with visitors and thus experience increases in the population, as opposed to the winter when a drop in the population occurs. Furthermore, the energy required by the system is directly related to the demand for water. Although the demand, according to the number of users of the network, makes up the most significant volume of water required by the network, the leaks present in the system play a primary role as sources of water loss. Then, optimising operations represents an opportunity for water utilities to lower energy consumption and implement sustainable operation systems. This study seeks to assess the drinking water distribution network's operation under such conditions, taking the city of Ebeltoft, region Syddjurs in Denmark, as the study case. Thus, this master project focuses on optimising the operation of the waterworks during seasonal changes, considering that pumping is the primary source of energy consumption. The degree project, which was carried out in collaboration with the consultant company Rambøll and the water utility Djurs Vand, provided all the relevant information to the project.

1.2 General aims and specific objects

The general aim of this study encompasses the energy consumption optimisation in the operation of waterworks during extreme seasonal variations in water demand between winter and summer. The selected study site involves one waterworks belonging to Djurs Vand Erhverv A/S in Denmark. More specific objectives for the study are:

- The development of a hydraulic model to simulate the operation of the distribution network operated by the waterworks, including model set-up, calibration and validation, with a main focus on pressure variations and pipe capacity.
- The analysis of the energy consumption for different scenarios with seasonal variations based on model simulations.

1.3 Procedure

To achieve the objectives of this project, a site visit was conducted at Egedal Vandværk. During this visit, relevant input data regarding the drinking water networks, including pipes, junctions, valves, plots, etc., was collected. This data was then used as an input parameter for the hydraulic model with MIKE+. The model setup was time-consuming, but once completed, the model was run. Data was collected simultaneously with pressure sensors and by retrieving data from SCADA (Supervisory Control and Data Acquisition) in the waterworks. This data was later used to calibrate and validate the model, ensuring its accuracy and reliability.

1.4 Limitations

It's important to note that while the report provides a detailed description of the pump operation at the waterworks, this setting was not included in the model. This omission, along with other assumptions and methods, was due to a lack of data in several parameters during the model set-up. For instance, interpolating pipe diameters was necessary. Apart from the pressure sensors installed throughout the network for around two weeks, the rest of the information available was based on centralised data at the pumping station level, which was a limitation to verify the flows and/or pressures at other points in the water distribution network. In addition, this study focuses on a steady state (flow conditions are constant and do not vary over time) and does not include transient flow analysis. These limitations, while they may impact the model's accuracy to some extent, do not undermine the overall validity and relevance of the study's findings.

2 Study area

2.1 Water supply network in Ebeltoft

The study area is located in Ebeltoft, a city part of the Municipality of Syddjurs in Mid-jutland, Denmark, as shown in Figure 2.1. The drinking water supply is led by the water utility Djurs Vand Erhverv A/S, which has to handle a situation where the population markedly varies over the year. The region of Jutland concentrates around 44 % of summer houses in all of Denmark (Andersen & Vacher, 2009), specifically, the coastal area of Ebeltoft which is well known for concentrating a large number of summer houses (NIRAS, 2008).

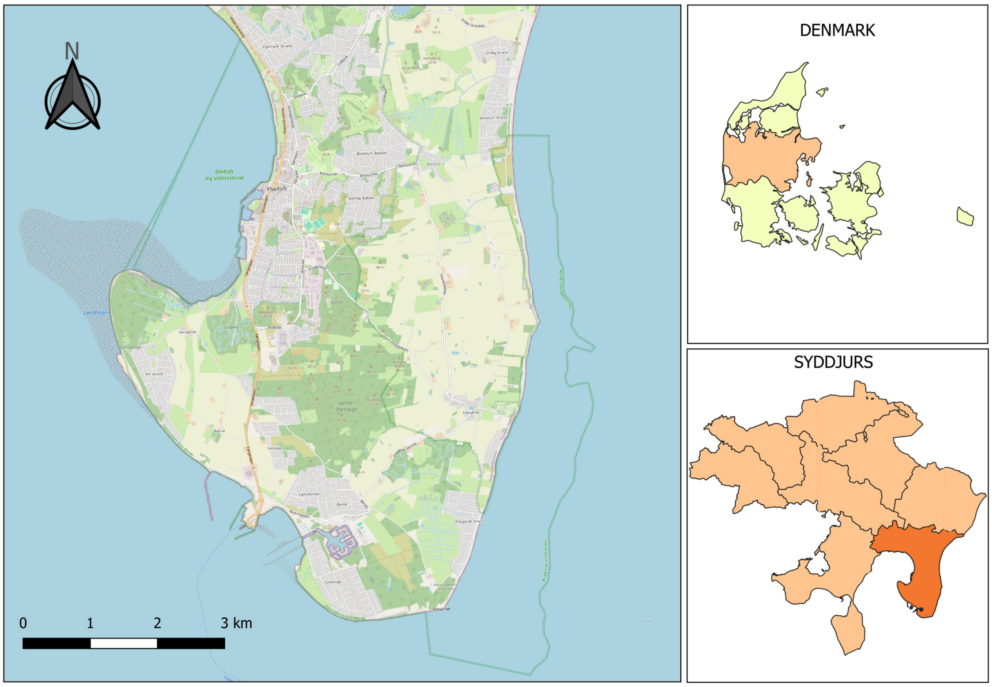


Figure 2.1. *Study area, Ebeltoft*

The water utility has one waterworks in Ebeltoft to supply around 3000 consumers with water, and where the seasonal variations in water demand represent a challenge to use the network efficiently. Djurs Vand has one water plant for water production in the study area: Egedal Vandværk. The drinking water supply area is illustrated in Figure 2.2, where the effective drinking water supply areas are highlighted with dark blue and framed with polygons (DjursVand, 2024). Based on the meetings held with the water utility team, the main interest in the study lies in the Hydraulic model as a tool to address several matters, such as leakage, renovation plans, critical pressure zones, seasonal consumption variations, and other issues that will be detailed in the next section.

2.2 Main issues

2.2.1 Leakage

Currently, the leakage percentage is around 10 %. Although the water utility has done a lot of work on leakage detection, they could not find so much because the pipes are mainly soft. That feature allows almost any noise to be identified, which makes it more difficult to detect leaks through methods like acoustic leak detection. Materials such as PVC and PE make it difficult to identify the sound compared to other materials such as cast iron.

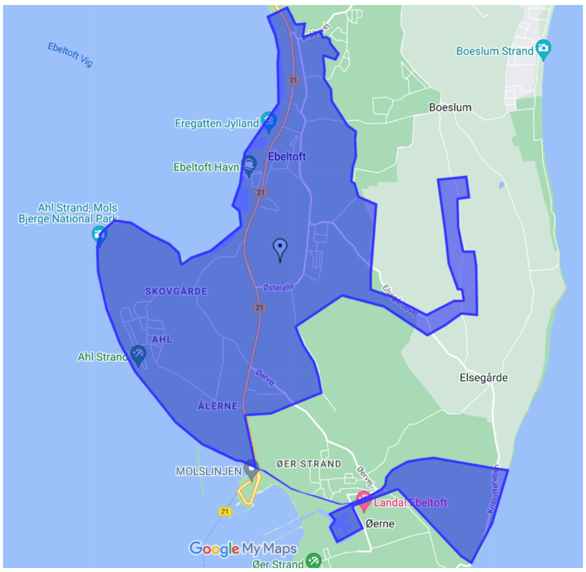


Figure 2.2. Egedal Vandværk supply area

2.2.2 Renovation Plan

Djurs Vand is carrying out a renovation plan due to old and over-dimensioned pipes (overcapacity), starting from the north to the south, from the edges and inwards. Figure 2.3 presents the drinking water supply network. Instead of ring attachments, they aim to replace them with string-attached piping. Some of the pipes were over-dimensioned because there was a water plant around that area 25 years ago. The pipes are still in use, but the water stream is reversed. The city council planned a big industrial area, but that did not become anything. The actual situation is that there are 250 mm PVC pipes for only 5 to 10 consumers. Although those plans are designed with around 75 years forecast, this projection is sometimes not achieved, as in Ebeltoft. Many years ago, around the 90's, the city had a big ferry harbour and a lot of industries, and the water production was 800000 m^3/year. Nevertheless, the current production is about 300000 m^3/year. The change in the city's development has resulted in an overcapacity in the system.

2.2.3 Pressure Zones

The most critical area where the water utility has more problems is where the hills in the topography play a significant role in the pressure variations. The pressure difference only based on the terrain level (gravitation) goes from 0.2 to 6.0 bar. Consequently, the area is divided into three different pressure zones: Zone 1, Zone 2 and Zone 3. In addition, there is one pressure-reducing valve (without this valve, the pressure could reach around 10 bar). The control of these zone valves is very sensitive because shutting down the valves or a wrong configuration would mean some areas with no water or pipe bursting. This will be addressed as part of the renovation plan, as the water utility plans to disconnect Zone 1 and Zone 2 because there is no option to connect both networks, which would mean getting too high or too low pressure.

Figure 2.3. *Egedal Vandværk drinking water pipes network*

2.2.4 Pumping optimization

Ebeltoft drinking water supply system does not have water towers (they used to have one, but they took it out due to contamination). Therefore, the plant controls the pressure; the pump outs are based on pressure sensors, a target pressure is set, and the pump's speed is adjusted. The distribution network has no pressure sensors, only in the waterworks where all the pressure is set from the pumps. This means that the water supply also relies on the power supply. However, the water utility has a generator for emergency power, and the pumping stations have a SCADA S2 automation system, which controls the pumps and backups to shut on. If the electric power goes down, the MPC hydro pumps are turned on.

2.2.5 Pipe bursts

In the town of Ebeltoft, the houses don't have any private reservoirs; the drinking water is provided directly from the network, which involves a higher level of responsibility for the water utility because, in case of problems, that would mean the consumers will not have any water. The water utility constantly pumps water out to the distribution network, having a pressure threshold set up which should be good enough to supply water to the customers, avoid sucking in air effects, and identify piping bursts quickly. Nevertheless, in case of a pipe bursting, the water utility closes the target section, and usually, reparations take around one to two hours. Zone 1 (including private houses and industry) is the area with the most consumers.

2.2.6 Variations in Demand

As Ebeltoft is well known for being a nice summer town, a lot of the area has vacation houses spread around the coastal areas and the main city. However, the city is also crowded with tourists during the summer season. Therefore, consumption is doubling from Easter to August. During the winter, the activities around the city slow down. A lot of the stores are closed for the winter. But, as soon as it is close to Easter, the city has much more life. There are about four or five times more people living in Ebeltoft. Then, the variations in consumption are due to two reasons: vacation houses and increased tourism during the high season. In normal season, the average hourly consumption is around 10 m^3/hour (around midday). However, the consumption also depends on the weather because there are a lot of gardens that use water for green gardens.

The previous sections listed the most relevant issues of interest to the Water utility. However, the current project will not address every problem aforementioned. Instead, this study focuses on hydraulic modelling to simulate the effect of leaks in the network under high- and low-season scenarios and their effect on energy consumption in drinking water distribution networks.

3 Methodology

The methodology employed to address the objectives is outlined in the following in terms of specific tasks that were carried out. In general, the main software and/or platforms used for the study were MIKE+, QGIS, Excel, Overleaf and AutoCAD.

3.1 Data compilation, collection and analysis

To carry out the hydraulic model relevant data in detail was required regarding the piping network and the components such as pipe dimensions, materials, joints and valves, as well as information about the pumping stations comprising the pump's type, model, capacity, and efficiency. All this data was provided as Shape Files by Rambøll and additional specifications by the water utility; then all the data obtained was inserted in MIKE+ to get a close representation of the system. Rambøll Graf online website was also used to consult the data, as the water utility updates any renovation carried out in such a platform. For the calibration and validation stages, pressure transmitters were allocated in five strategic locations along the network.

3.2 Hydraulic model development

The hydraulic modelling was performed using a model developed by DHI under the commercial name of MIKE+ (DHI, 2024). The modelling will focus on steady-state conditions, as the time variations are slow and possible to neglect in the analysis of optimal system performance. As pumping is deemed the primary source of energy consumption, it will be essential to quantify the energy losses in the system. The model was set up, calibrated, and validated according to the objectives and available data. For the calibration and validation stages, pressure measurements were conducted through the installation of five data loggers in the network for approximately two weeks. Meanwhile, the water utility provided the flow and pressure measurements downloaded from SCADA from the pumping stations. Following the model validation, relevant scenarios will be simulated according to the seasonal variations to identify opportunities to minimise energy consumption by reducing energy losses and identifying additional critical areas in the system.

4 Model set-up

4.1 General Settings

The model was configured in different stages addressing all the system components which are described in each section of this chapter. General settings included the Water Distribution model and DHI EPANET 2.2 for all the simulations. The Coordinate System used in the model is ETRS89 / UTM zone 32N. For each step of the modelling process, different data sources were reviewed which included: Rambøll Graf online website, paper plots, and shapefiles. In the case of inconsistencies or missing data meetings were held with the water utility to clarify such matters. The data included some pipes located in areas outside the scope of the study and pipe types not relevant for the modelling (e.g. service pipes), which were disabled. Data outside the study area or not relevant to the model was disabled in MIKE+.

4.2 Topography

The topography of the study area is input data required to identify the elevations of all the components, such as junctions, tanks, etc. This is because the pipes network is installed underground at the surface level. Therefore, to model the topography of the study area, a Tag Image Format (TIF) file was downloaded from SCALGO for the terrain and then imported as a layer in the project. The data from SCALGO served as the reference layer to interpolate the surface level (Z)(illustrated in Figure 4.1, for network elements such as the junctions and tanks. Additional specifications regarding pipe depths or elevations were included and then MIKE+ performed the relevant calculations.

4.3 Pipes

The pipes setup in the model was based on the shapefile provided by Rambøll, which contained the database of several features (named sub-

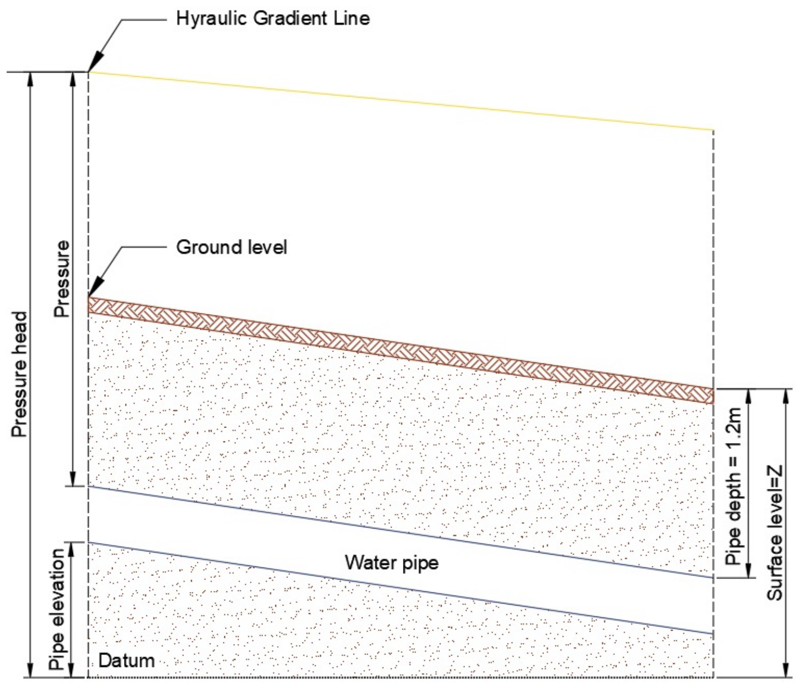


Figure 4.1. *Concepts in the model*

classes) such as dimensions, diameter, material, etc. The data included some pipe types not relevant for the modelling (e.g. service pipes, raw water pipes, etc.), which were disabled. Additional pipe connections were added to the model as a group of pipes was found to be not connected to the network. Regarding the pipe depth, it was assumed a constant value of 1.2 m below the ground surface (illustrated in Figure 4.1).

4.3.1 Material

The pipe materials in the distribution network are mainly Polyethylene (PE) and Polyvinyl chloride (PVC), although, there are also Carbon Steel (STE) pipe stretches and data with unknown pipe material. A parameter regarding the material properties considered in the modelling is the Standard Dimension Ratio (SDR), which is a specification to rate pressure on pipes and refers to the ratio of the outside diameter to the pipe wall thickness (Toolbox, 2006). With higher SDR values, it's likely to have a thin pipe wall and therefore a lower nominal pressure could be expected. For the study case, a constant SDR 17 is assumed for all the pipes and Pressure Nominal (PN) 10.

4.3.2 Diameter

A lack of data regarding the diameters was identified on the provided shapefiles; many pipe diameters were missing in the aforementioned file. All the available sources were reviewed but no information was found. Therefore, in the case of the 222 pipe diameters missing, a MIKE+ interpolation tool was applied to fill in the missing information based on the nearest feature. Moreover, 11 pipe diameters were assigned manually considering the neighbour diameter pipes. These small groups of pipes were easy to identify as a result of the MIKE+ pipes processing and/or error in the GIS file, which included pipes overlapping, disconnected pipes, etc. Nevertheless, to track such pipes in the future, the status for all the assumed diameters was changed to "modified" with notes in the model. The interpolated and assumed values were considered the right values due to the lack of data.

The pipe wall thickness was updated in the model for all the diameters according to the materials. In the case of PE pipes (which included: PEH, PEL and PEM), 1242 items were modified, based on the catalogue of one pipe production company (WAVIN, 2023). For Steel pipes, the internal diameter is provided in the data by default. Consequently, the inner diameter was calculated by MIKE+. The assumed wall thickness for all the pipes according to the diameter is shown in Table 4.1.

Table 4.1. *Assumed wall thickness for pipes, PE*

Diameter (mm)	**Wall thickness(mm)**	**Inner Diameter(mm)**
32	2.0	28.0
40	2.4	35.2
50	3.0	44.0
63	3.8	55.4
75	4.5	66.0
90	5.4	79.2
110	6.6	96.8
125	7.4	110.2
160	9.5	141.0

4.3.3 Roughness

The pipe roughness is a mandatory parameter assigned to the model. The roughness is related to the pipe material (and construction year). Friction losses in hydrodynamic calculations are based on pipe roughness. Head losses are calculated as a function of the flow rate in a pipe, where the roughness is a variable (DHI, 2024). The head loss formula chosen is Darcy-Weisbach, with its corresponding roughness coefficient. The software has a table with default coefficients according to the formula and material in the Hydraulics section of pipes. Taking into account the reference values proposed by MIKE+, two different roughness values were applied, 2.5 and 0.0025 mm, for materials carbon steel and plastic, respectively.

4.3.4 Flow and pressure

Five pressure transmitters were installed in February 2024 to measure the pressure flow in the pipes. Because the calibration requires data without disturbance, this period was chosen to represent the model under normal operating conditions, avoiding holidays and the beginning of the high season.

4.4 Valves

The provided database contained the locked open and closed valves, this is based on the valve open-closing plan, which has been constant at least during the years 2022 and 2023. The model was set up with 603 valves, mainly gate valves. Although the network has several stopcocks, these are located in service pipes which were disabled and, therefore, not considered in the model. According to the plan, 20 valves are closed, which was set up in the model; the remaining valves have all opened fixed status. This information is very sensitive as the correct configuration of all the valves in the network is of vital importance because any misalignment in these valves can mean pipe bursting in areas where the pressure can reach 10 bar.

4.4.1 Isolation or Gate Valves

Although the database containing the hydraulic network initially had 630 gate valves, only 523 gate valves were included in the model. That selection was made based on some identified errors, such as overlapping, location outside the distribution pipe, valves in service pipes, etc. All the Gate valves were modelled as General-Purpose Valves (GPV) in MIKE+, with a setting type loss coefficient and a specific Headloss curve, Flow (Q) vs Head (H). The database also contained other types of valves counting for 79, which were included in the model as GPV.

4.4.2 Pressure Reducing Valves (PRV)

PRV regulate a high inlet upstream pressure to a predetermined outlet downstream pressure. There is one pressure-reducing valve in Zone 2, according to the water utility team, this is an old valve from the 80s. The boundaries of the pressure-reducing valve are inlet pressure of 4.5 bar and outlet pressure of 3.5 bar.

4.5 Pump stations

Due to differences in the terrain level, the drinking water supply area in charge of the water company is divided into three pressure zones, as can be seen in Figure 4.2. Egedal Vandværk has three pump stations with 8 pumps in total. The first pump station supplies water for Zone 1, whereas the second pump station is for Zone 2. These two pumping stations are located at the waterworks. The specific location of each pump station is summarised in Table 4.2.

Table 4.2. *Pump station locations*

Description	Zone 1	Zone 2	Zone 3
Latitude	56° 11' 1.05" N	56° 11' 1.21" N	56° 11' 52.836" N
Longitude	10° 41' 20.09" E	10° 41' 19.83" E	10° 41' 33.72" E

According to the data provided by the Water company, there is only one tank whose volume is 750 m^3, with a height of 2.5 m. The tank which has no dividers in it, supplies water for both pumping stations. In the model, the tank geometry was assumed as rectangular with a length of 30 m and a width of 10 m. The water storage tank was created with a constant Hydraulic Grade Line (HGL) and fixed reservoir level type to simulate a reservoir where the water is endlessly available during all the simulations (DHI, 2024). In MIKE+, water tanks are simulated as nodes, therefore the Surface Level (Z) was obtained by interpolation using the TIF file. Afterwards, the maximum level and the Fixed HGL were set to the same level as the surface level, being Z = 36.26 m. The base elevation was set

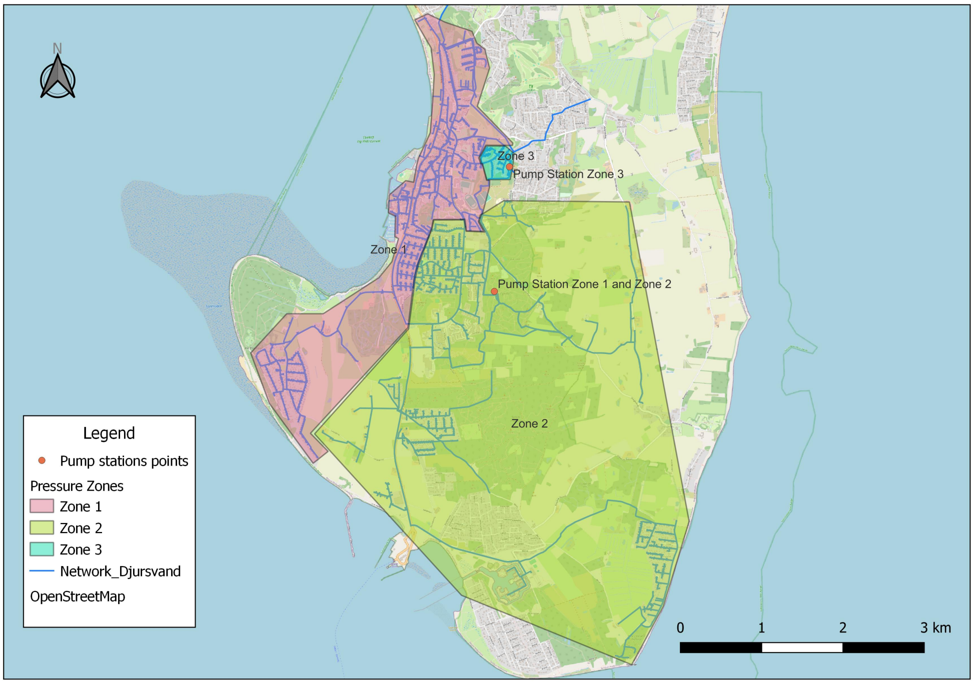


Figure 4.2. *Pressure Zones*

to 33.76 m. These dimensions are represented in Figure 4.3.

In the case of Zone 3, the pump station is pressure enhancement, where there are no tanks only two pumps. This booster station is not located in the waterworks but around Zone 3 itself. All pumping stations have Grundfos brand pumps, detailed information regarding the type and model of the pumps is presented in the subsections. All the pumps are vertical, centrifugal and multistage based on the information retrieved from Grundfos, the pump manufacturer. As part of the assumptions the pumped liquid is water at a liquid temperature during operation of 20 °C.

4.5.1 Zone 1

The pump station for Zone 1 has three parallel pumps as can be seen in Figure 4.5. The centrifugal pumps are operated with VLT Automation Drive (Danfoss). The drinking water is pumped out from this station towards Zone 1 at a pressure service of 1.8 bar. The pump set is a HYDRO MPC (Grundfos), the pump specifications for all zones are presented in Table 4.3, whereas the pump and efficiency curves for all the

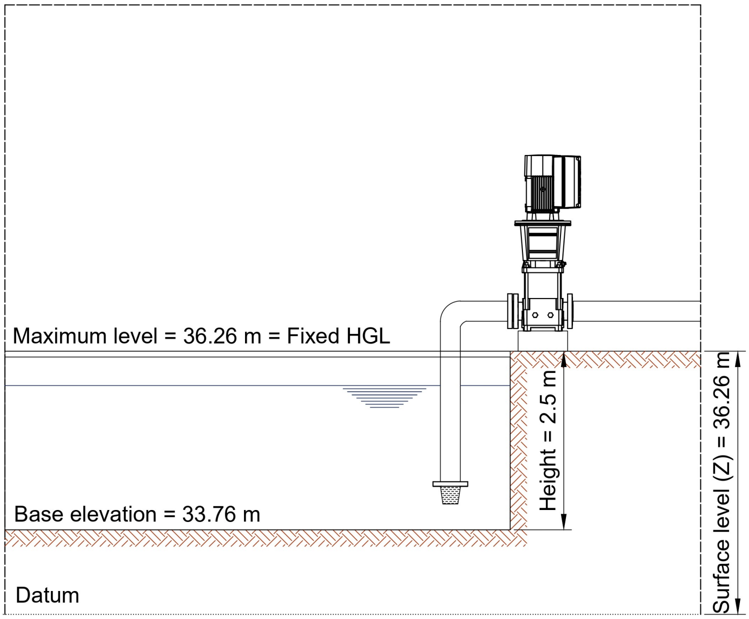


Figure 4.3. *Water tank diagram. (Pump drawing source: GRUNDFOS-a, 2024)*

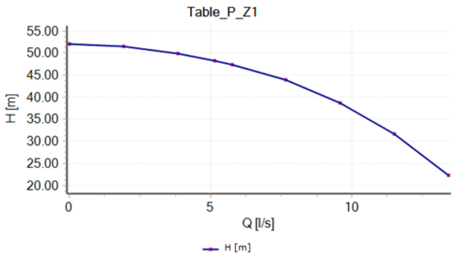
Figure 4.4. *Djurs Vand office in Ebeltoft*

zones are presented in Figure 4.6, detailed information was retrieved from GRUNDFOS-a, 2024. All the aforementioned data was inserted as Tables in the model, after which the pumps were created in MIKE+, represented as links. In the case of the zone 1 pumping station, the starting node was located in the tank while the final node was in the discharge pipe whose diameter is 225 mm. As part of the pump properties, the type was set to Variable Speed Drive (VSD) as the pumping varies according to the demand. The control type chosen was Downstream Node Control, which allows the variable speed to be commanded by a pressure control downstream of the pump discharge. The control level type is by pressure whereas the control pressure was 1.8 bar. The minimum and maximum relative speeds (coefficients) were set to 0.2 and 1.2 for all the pumps.

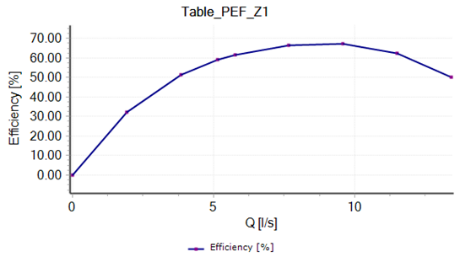
Figure 4.5. *Pumps and flow meter in pump station Zone 1*

Table 4.3. *Pumps specifications for Zone 1, 2 and 3*

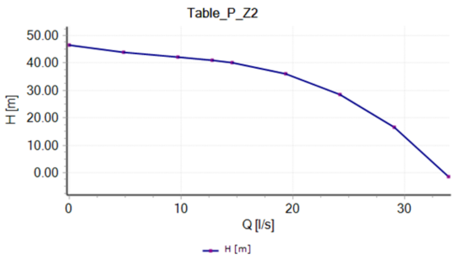
Description	**Zone 1**	**Zone 2**	**Zone 3**
Type	CRE32-2-1 A-F-A-E-HQQE	CR90-2-2 A-F-A-E-EUBE	CRIE 10-5 A- CA-A-E-HQQE
Model	B96122660P11445	A96410877P3 00510002	PN-SN A-99071462- 10002623



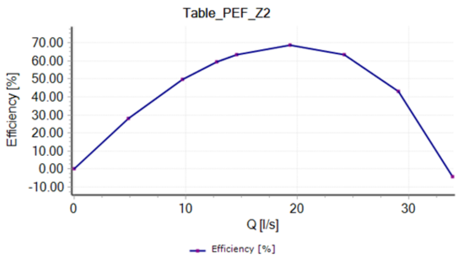
(a) Pump curve, Zone 1



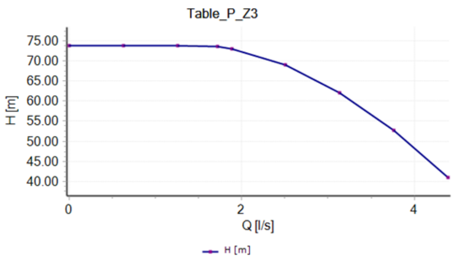
(b) Efficiency curve, Zone 1



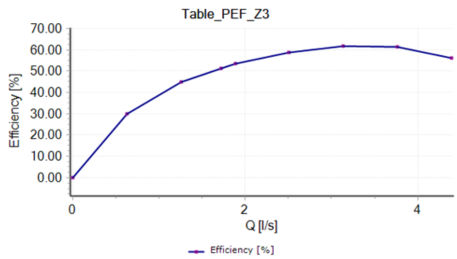
(c) Pump curve, Zone 2



(d) Efficiency curve, Zone 2



(e) Pump curve, Zone 3



(f) Efficiency curve, Zone 3

Figure 4.6. Pump and efficiency curves for pumps for Zone 1, 2 and 3

4.5.2 Zone 2

Zone 2 has two parallel pumps controlled by the Hydro MPC and VLT Automation Drive (Danfoss), as shown in Figure 4.7. However, the MPC unit is a secondary choice because the SCADA S2 is controlling which pump it's a backup system. Then in case the S2 is gone down, a switch over to the MPC unit is done. This configuration was chosen based on some difficulties in case the electric power goes down, which generates that the Frontmatec system, has a long time to start up, whereas the MPC starts momentarily. The water utility has a generator for emergency power that goes for about 7 seconds, the MPC unit starts up in about 2.5 minutes, and the S2 SCADA uses 5 to 10 minutes, so when it does not get a bus signal from the SCADA, then it goes over to the MPC unit. The waterwork does not have a night pump, the system goes lower. The configuration is set for an energy-optimising system, where there is constant looking for flow and pressure and assessing the most economical option, for instance, if it is better to run two pumps at 60 % or one at 90 %. In addition, for the pumps with the VLT, a default setting was programmed if the bus signal is lost and they do not have any pressure sensor feedback, then the pumps are automatically going on 60 %. All the pumps have frequency convertor devices which are set to work up and down according to the target pressure coming from the pressure sensors. The water is pumped out from the waterworks towards Zone 2 at a pressure service of 3.5 bar.

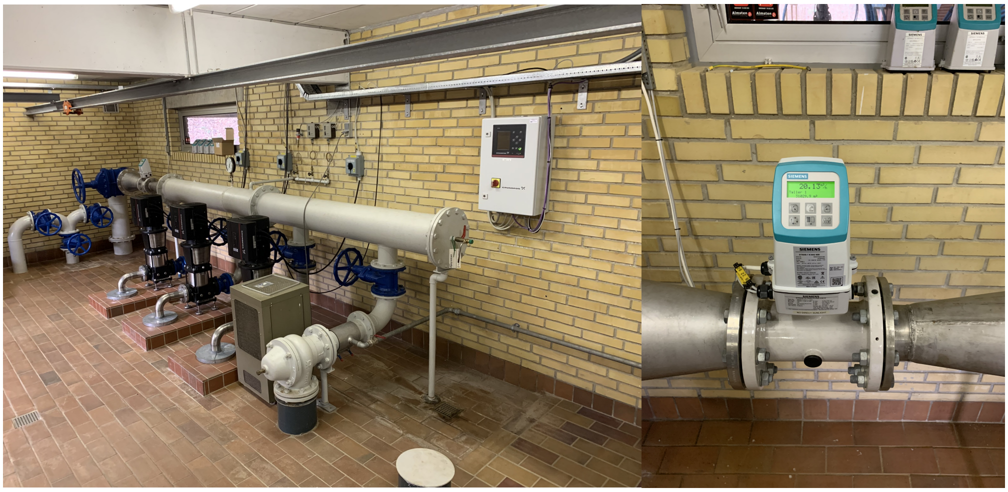


Figure 4.7. *Pumps and flow meter in pump station Zone 2*

The pump specifications for Zone 2 are presented in Table 4.3. Although the manufacturer discontinued this type, a similar pump with another shaft seal (HQQE instead of EUBE) was taken into account for the modelling, and detailed information such as the curve pump was retrieved from GRUNDFOS-b, 2024. Relevant information regarding the Q-H and pump efficiency curves (Flow and Head) (Figure 4.6), was added as tables in the model, whereupon the three pumps were created in MIKE+. Similar to the Zone 1 configuration, in the Zone 2 pumping station the tank is the starting node whereas the discharge pipe, whose diameter is 160 mm, is the final node. In the pump properties section, the type was set to Variable Speed Drive (VSD), the control type chosen was Downstream Node Control, the control level type selected is by pressure and the control pressure was 3.5 bar. Although the discharge pipe diameter is 160 mm, afterwards, this pipe is divided into two pipes of 225 mm and 160 mm diameter. This information was discussed and assumed as correct although this has not been confirmed by field work by the water utility.

4.5.3 Zone 3

This pressure sector has a pressure enhancement pumping station located outside the main waterworks. Although this sector covers a small area of land (almost part of Zone 1), it is also the highest point of Ebeltoft. The pressure at the top of Zone 1 is 0.2 bar, then a booster station is needed to raise the pressure to 3.5 bar to supply drinking water in such area, otherwise, the highest consumers would not have any water pressure at all. The Twin Pump Booster set type and model can be shown in Table 4.3, whereas the pump curve is presented in Figure 4.6. Detailed information was retrieved from GRUNDFOS-c, 2024. The supply and discharge pipeline diameters are 160 mm and 110 mm, respectively.

4.6 Water consumption

The water utility provided the consumption data needed for the demand modelling, as the allocation is very specific according to the user's distribution. The daily values from the consumers registered in the flow meters were data from 2022. The water company stated that it was more convenient to use data from the year 2022 because, during the year 2023, the flow meter suffered a lightning strike failing a flow transmitter. In addition, there were no changes in the piping during 2023; therefore, the results should be the same. The number of consumers based on the flow meters are 1855, 986, and 101 for Zone 1, Zone 2 and Zone, respectively.

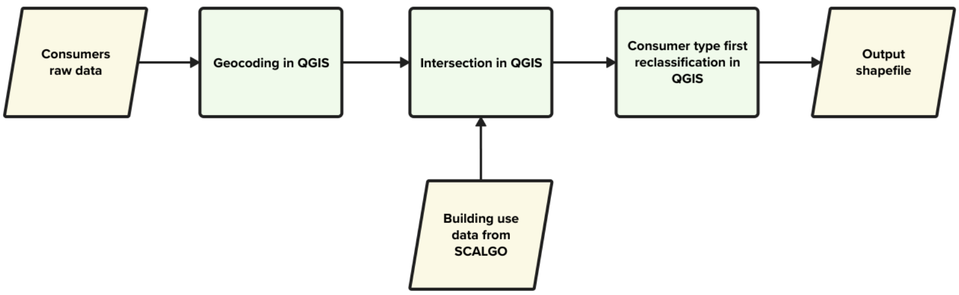


Figure 4.8. *Consumers data processing flowchart*

However, the demand modelling was carried out with data provided by

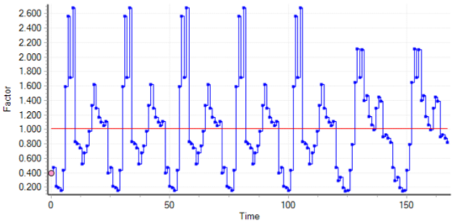
Rambøll for the year 2022 as a Text file containing the user's addresses and their yearly consumption. The data was cleaned, as some characters were distorted when these were exported. The initial data did not include coordinates but addresses, therefore a conversion to latitude and longitude values was required through geocoding. First, the data was geocoded in QGIS with a plugging MMQGIS, using the Geocode CSV With Web Service tool. The geocoded file was updated with information retrieved from SCALGO regarding the building use and then reclassified into seven different Demand Categories. Along with this data processing, some consumer points were edited due to errors in the geocoding, lack of information and other inconsistencies. The aforementioned steps are shown in Figure 4.8.

4.6.1 Consumers categories and patterns

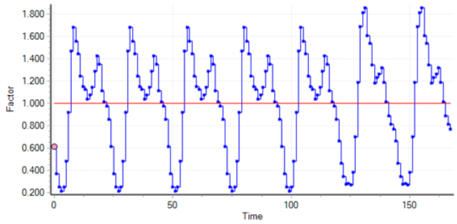
The output shapefile was imported to MIKE+ to define the demand allocations. The demand allocations were connected to the node by the nearest enabled pipe, avoiding disabled pipes such as service pipes. Afterwards, the aggregation tool was used to assign demands to multiple demands. In addition, seven different patterns were created in MIKE+ matching the description given for the Demand Categories. These patterns were named: Residential, Multi-residential, Summer house, Industrial, Institution, Commercial, and Other (e.g. agriculture, unknown consumers, etc.). This input data was created on a weekly basis (168 hours), with information retrieved from Miljøstyrelsen, 2005 and information provided by Rambøll. The demand patterns can be observed in Figure 4.9.

4.7 Preliminary Results

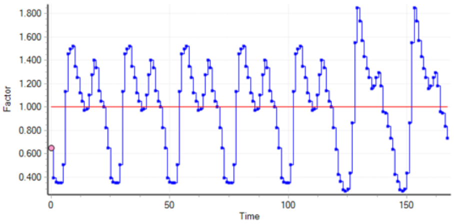
Based on the valve open-closing plan, 20 valves are closed. Running the model under such conditions implied a loop and backflow conditions, making it impossible to switch on the pumps for Zone 1. Therefore, two valves were closed to make Zone 1 independent from Zone 2, whereas one valve was closed in Zone 3 to increase the outlet pressure from the booster station. In total, three additional valves were closed to stabilize the model. Although the system has an energy-optimization configuration during the night hours, this was not set up in the model.



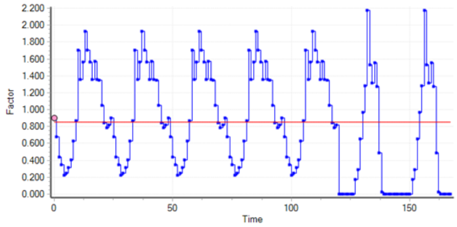
(a) Residential



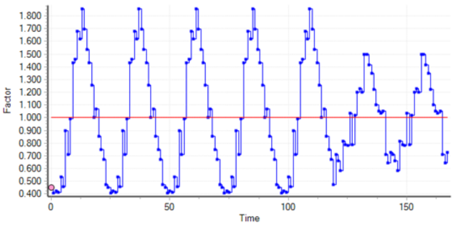
(b) Multi-residential



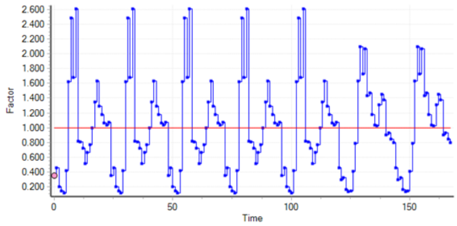
(c) Summer house



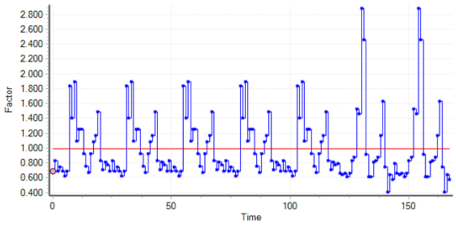
(d) Institutions



(e) Commercial



(f) Industry



(g) Other

Figure 4.9. Consumers patterns

4.8 Leakage modelling

The leakage modelling was performed after the model was run, calibrated and validated. The ideal scenario for waterworks would be a perfect match between the water production at the waterworks and the water demanded by consumers. However, this relationship is never fulfilled due to leakages. An easy and very well-accepted method to quantify leakages is through percentages to represent how much water is lost in the system (Puust et al., 2006). Considering that the objective of hydraulic modelling is related to energy optimisation and the study area's conditions, where leaks are around 10 % of the total demand, a leak analysis was included in the model. Although, on average, the leakage in Denmark was set to 7 % in 2021 (DANVA, 2022), there are drinking water companies with higher and lower values than this average, fluctuating between 1 to 15 % approximately; then a 10 % water loss was assumed as the water utility stated it. The most significant parameters considered in the leakage modelling are pressure, pipe age and material (Saghi & Aval, 2015).

Pressure is the most predominant factor in modelling leaks in pipes. The behaviour of pipe cracks is directly related to pressure variations; at higher pressure, the pipe fissures tend to open more and lose more water, while at lower pressure, they tend to close(Saghi & Aval, 2015). Similar behaviour can be expected in the joints or unions between pipes and other water network components. Hence, the first stage of the study is essential in generating a hydraulic model that simulates the pressures throughout the drinking water distribution network. The based model simulation results regarding pressure in the nodes were used by identifying all nodes with pressure higher than 45 mwc, which accounted for 1850 nodes, as the first criterion.

The second condition considered the pipe's age when selecting all the pipes installed before 2000, and the number of pipes under this criteria was 2482. The last condition was based on the material, and according to the data provided, the primary materials in the network area are PVC, Steel, and PE. However, PE pipes were excluded from the target group, and the number of pipes was 2241. In addition, all the unknown input data regarding pipe age and material were also included in the target group.

The leakage modelling in MIKE was performed by selecting the 27 junctions that met the criteria above regarding pressure, pipe age, and material. These junctions were modelled as emitters, as depicted in Figure 4.10, where the star-blue icons represent the emitters. As the leakage is modelled through emitters, the flow is pressure-dependent according to Equation 4.1. The flow coefficient is determined in flow units per 1m pressure drop in this equation (DHI, 2024). The default value for the emitter exponent (E) in MIKE+ is 0.5, mainly to represent nozzles and sprinklers, but it is recommended to be modified in case of leakage modelling (DHI,

Figure 4.10. *Emitters scattered to simulate pipe leakage*

2024).

Although research has been conducted to assess the emitter exponent according to the type of leakage and material, the most suitable parameter value for this study case was 0.3, based on trial and error. In addition, this emitter exponent must be set for the entire network in the simulation setup. On the other hand, the flow coefficient was found to be a parameter very sensitive to low values in MIKE+ (Gupta, 2017). Different flow coefficient values were tested manually in the simulations (from 0 to 0.0021). The best flow coefficient value tested was 0.0021 to reach the 10 % leakage, equivalent to a flow 0.88 l/s. The model with leakage considerations yielded a flow of 9.7 l/s, close to the production average value of 9.85 l/s, based on the fourteen days of data extracted from the flow meters in the waterworks. Nevertheless, based on yearly data recorded by flow meters in the water utility, the average demand is 10.7 l/s. In contrast, the corresponding parameter based on the data used for the model was 10.3 l/s.

$$q = (FC)P^E \tag{4.1}$$

Where:
q: Flow out of the emitter(l/s)
FC: Flow coefficient or emitter coefficient (l/s/m)
P: Pressure (mwc)
E: Emitter exponent

4.9 Energy consumption

The power required by the pumps highly relies on the pumps efficiency as it is shown in Equation 4.2. However the pumps efficiency highly varies along the day as the demands vary every hour. Based on the SCADA data the variations are from 1 to 6.5 l/s for Zone 1, whereas Zone 2 the variations are from 0 to 4 l/s. The energy price considered in this study is 0.35€-kWh (Denmark, 2024).

$$P = \frac{QHg\rho}{3600\eta 1000} \tag{4.2}$$

Where:
P: Power (kW)
Q: Flow coefficient or emitter coefficient (m^3/h)
H: Head (mwc)
g: Gravitational constant (m/s^2)
ρ: Water density (kg/m^3)
η: Efficiency (%)

5 Model Calibration and Validation

5.1 Data compilation

The data for the calibration was recorded in 5 pressure loggers KELLER, type LEO Record as seen in Figure 5.1. The loggers with specific serial numbers were located in different areas around Ebeltoft, as summarised in Table 5.1. Data recording was carried out for a time interval of two weeks. Two different starting days are considered according to when the loggers were installed: the 29th of February and the 1st of March of 2024. The time step was set to every 5 minutes, recording at least 5218 values per device. The pressure data was recorded in mbar. The data recorded on the sensors were downloaded using the LOGGER 5 software, and the logs were converted to an Excel XLS file and then exported. In addition, flow and pressure data regarding the pumps for Zone 1 and Zone were downloaded from the SCADA with a starting date of 27th of February. For Zone 3, only pressure data was retrieved. The exported files were input values for creating the times series and measurement stations in MIKE+ for the following stages.

Figure 5.1. *Pressure loggers*

In total, ten measurement stations were considered for the calibration and validation stages, as depicted in Figure 5.2. Five stations were located according to Table 5.1, whereas the remaining were located in the pumping stations For Zone 1, 2 and 3. Separate data series were considered, one for flow rates and another for pressures. Regarding the pumping station for Zone 3, only pressure data was available.

Table 5.1. *Pressure loggers locations*

Logger ID	Address	Description
11723	Kristoffervejen 34C	Consumer
10654	Bakkehegnet	Skelhøjevej / Bakkehegnet
11722	Lejrskole	For enden af Birkestien ved Ahl
10650	Cirkel-K, Strandgårdshøj	Vibæk strandvej/Strandgårsdhøj
10651	Mariendalsvej 5	Consumer

Figure 5.2. *Calibration/Validation points locations*

5.2 Calibration

The calibration process, a crucial step in maintaining the hydraulic system's accuracy, was meticulously executed. In summary, the calibration procedure included using pressure loggers and SCADA data as input data to run the model under the Extended period hydraulic (EPH) module. Then, the measured and computed trends were compared. Afterwards, several parameters were modified (such as the pumps' speed, the pipe's roughness, water demands, etc.) to best match the measured and computed values. The calibration was performed without leakage conditions and under low-season conditions. The calibration and later validation stage results gave rise to the base model. The procedure followed to calibrate the model is mentioned in detail below.

The data recorded in the loggers was split into two sets, with 60 % reserved for the calibration stage and the remaining for validation. To ensure a complete data set, only data with overlapping days (corresponding to six days from the 1st to the 7th of March) were used for the calibration. The data in the measurement points created the time series in MIKE+. Such data was paired with the model results according to the parameters type (flow or pressure).

The model was then simulated under the Extended period hydraulic (EPH) module. The calibration was performed initially with the flow time series from Zone 1 and Zone 2 pumping stations. The flow simulated values were too high compared to the loggers data. Therefore, the peaks were modified to match the simulated and measured values. This calibration was done mainly for Zone 1, applying a coefficient of 0.6 to all the demand patterns, whereas for Zone 2, the coefficient was 1. Initially, the pump settings, such as relative, maximum, and minimum speed, were assessed under different conditions. Nevertheless, the default values were maintained. When the flow computed values in both pumping stations followed the same pattern as the measured data, the pressure data also coincided. In the case of the booster station for Zone 3, only pressure data was provided. Then, different alternatives were tried during the calibration, including closing valves and adding a flow control valve to control the backflow coming from 200 and 225-mm pipes. However, the pumps require a high flow to deliver 3.5 bar. Critical conditions were kept because this high flow rate increased the outlet pressure.

Once the model was calibrated for the pumping stations, the focus shifted to the measurement stations scattered across the study area. These stations played a crucial role in fine-tuning the model and ensuring its accuracy across the entire system. Along the five measurement points, the target parameter was the pressure, which, in general, was underestimated. The pipe roughness and the valve curve head-loss settings were modified to increase the pressure in such areas and reduce friction losses. In addition, the demand patterns were reduced by multiple demands in these target areas to increase the pressure.

Overall, the calibration process involved a significant amount of trial and error. This iterative approach was necessary to fine-tune parameters such as pipe roughness, demand patterns, valve head-loss, and pump settings (relative speed) to achieve the desired results in different areas, most of which required increased pressure. Despite an auto-calibration tool in MIKE+, it was not used during the calibration stage, highlighting the commitment to a hands-on, meticulous approach.

5.2.1 Calibration Results

The calibration results for the ten measurement stations are presented from Figure 5.3 to Figure 5.12. For Measurement Station 1 (illustrated in Figure 5.3), located north of the study area, the computed data follows the pattern of the measured data except during the night hours, where the calculated peaks stand out on the plot, being the computed value 48.93 and the estimated value 50.41 mcw, mainly from 22:00 to 06:00 hours. The difference between both values is 1.48 mwc, a meagre value. This could be addressed by setting up real-time and rule-based control during night hours, as it is set up in the waterworks. However, this control was partially included in the model but can not simulate completely the energy-saving programming from the automation devices.

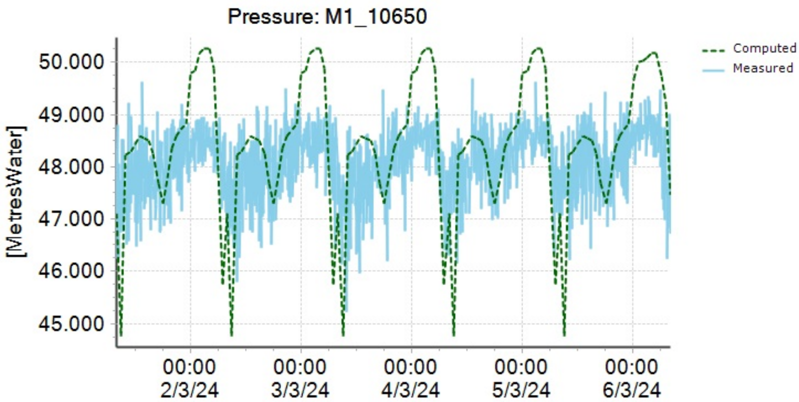


Figure 5.3. *Calibration Measurement station 1 (M1), logger ID 10650*

In the case of Measurement Station 2 (shown in Figure 5.4), even though the computed values have a similar trend as the measured data recorded in the loggers, the pressure is around ten mwc lower, being this area the one that least coincides about the general calibration of the model. It was observed that a mix of water between Zone 1 and Zone 3 occurs in this area. Another possible explanation for this lag could be that some valve is closed or throttled in the network, which would cause the pressure to be higher in said area.

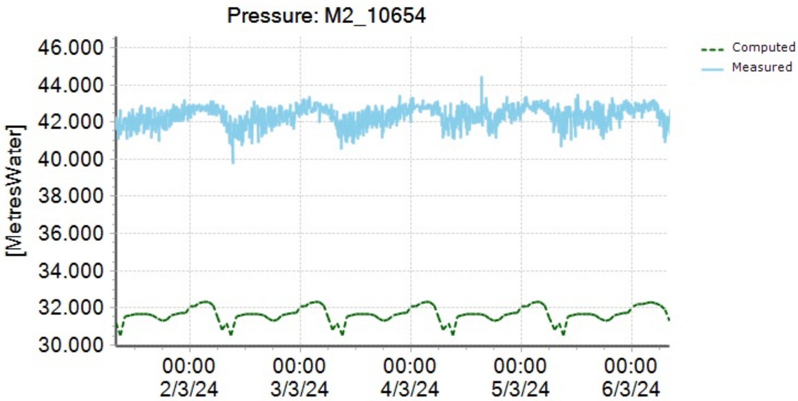


Figure 5.4. *Calibration Measurement station 2 (M2), logger ID 10654*

The pressure pattern for the computed values in Measurement station 3 is slightly below the average measured pressure, as shown in Figure 5.5. This station is located north of zone 2, in one of the last areas of the water supply network. Similarly, measurement station 4 shows a similar pressure values trend concerning the measured data but moderately below the same. This can be observed in Figure 5.6.

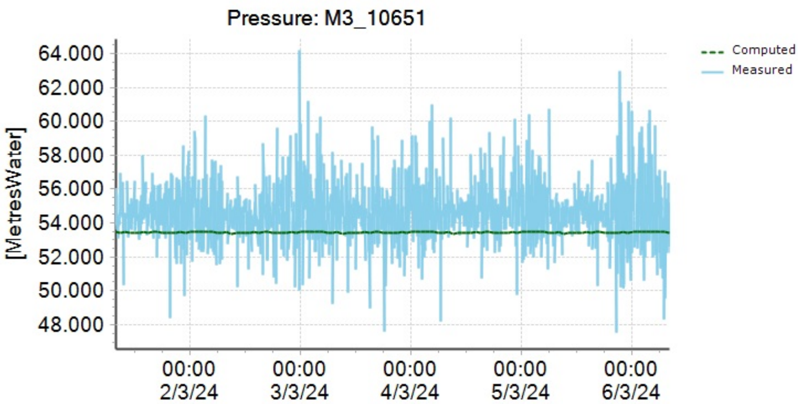


Figure 5.5. *Calibration Measurement station 3 (M3), logger ID 10651*

A particular situation occurs at measurement station 5, where the trend of

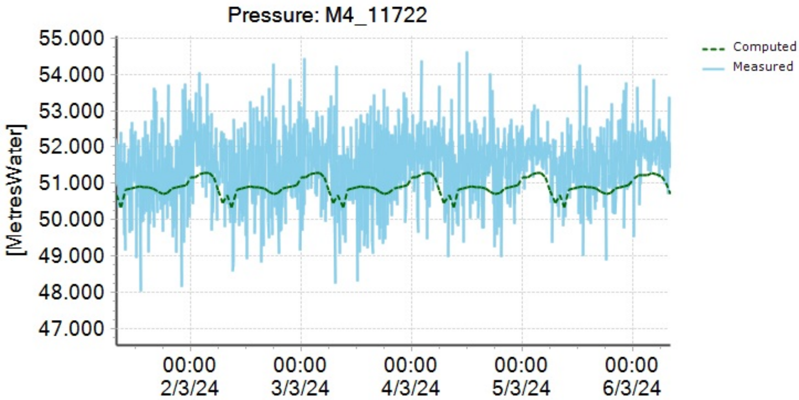


Figure 5.6. *Calibration Measurement station 4 (M4), logger ID 11722*

the simulated data series fits the measured data quite well, as illustrated in Figure 5.7. This is because at the beginning of the supply network for the said area, there is a pressure regulating valve, whose boundaries are inlet pressure 45 mwc and outlet pressure 35 mwc. Then, the pressure is controlled in such an area.

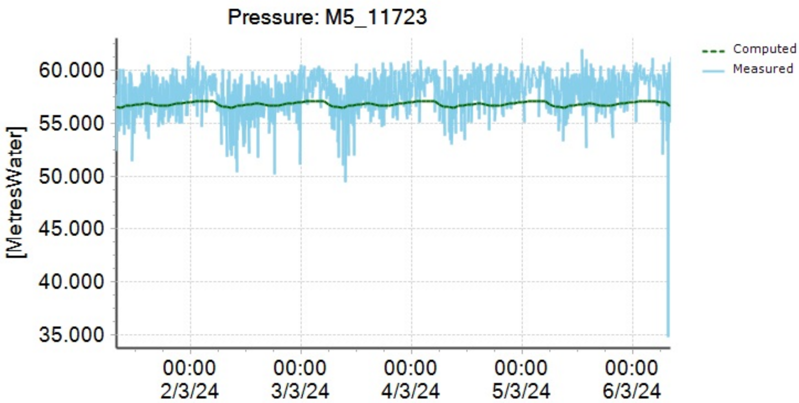


Figure 5.7. *Calibration Measurement station 5 (M5), logger ID 11723*

Measurement stations 6 and 7 are located in the waterworks and record flow and pressure data series, respectively. The model reads pressure in the junctions or nodes, whereas flow is read in pipes or links. Flow and pressure patterns are accurately represented in the simulated values compared to the measured data (as can be seen in Figure 5.8 and Figure 5.9), with flow peaks around 6.5 L/s and a pressure of 18 mwc.

The pumping station for Zone 2 was the location of measurement stations 8 and 9, which recorded flow and pressure, respectively. Although the

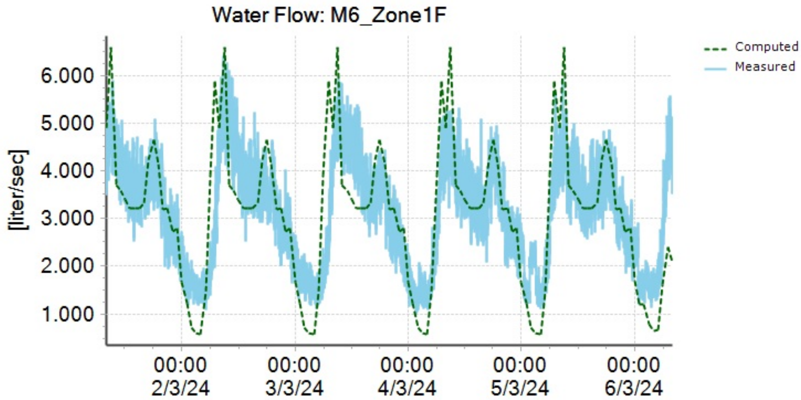


Figure 5.8. *Calibration Measurement station 6 (M6), Zone 1 flow data*

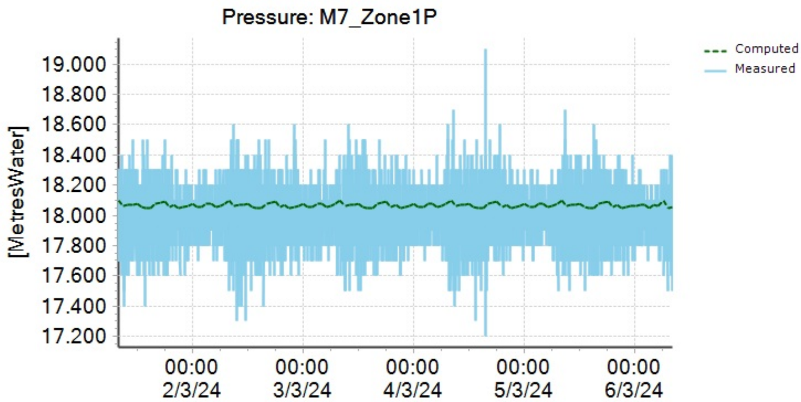


Figure 5.9. *Calibration Measurement station 7 (M7), Zone 1 pressure data*

flow pattern in measurement station 8 is more noisy than in station 6, the model still follows a similar trend, with flow peaks of around 4 L/s. In the case of pressure-simulated values, the pressure varies between 17.5 and 18.5 mwc. In Figure 5.11, it can be observed a high-pressure variation during night hours.

Finally, in the case of the pressure enhancement station for Zone 3, only pressure data was assessed, as illustrated in Figure 5.12, where the simulated pressure follows the same pattern as the measured data.

Overall, the base model performance has an average total demand of 8.8 l/s; however, according to the data recorded by the flow meters in the waterworks, the water production is 10.7 l/s. Then, an additional analysis was included, taking into the results from the base model. As the model

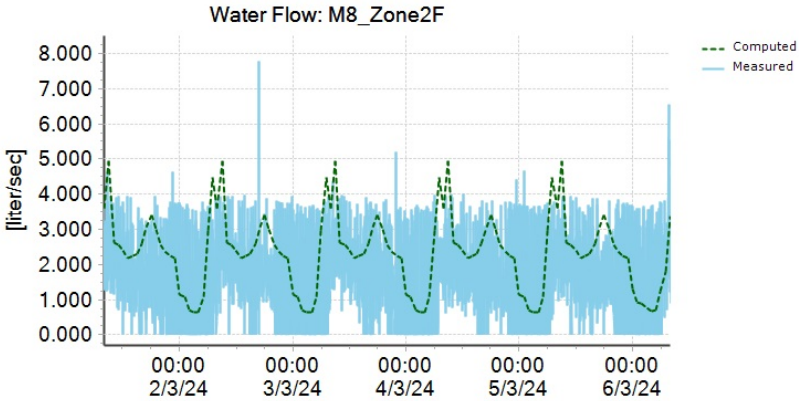


Figure 5.10. *Calibration Measurement station 8 (M8), Zone 2 flow data*

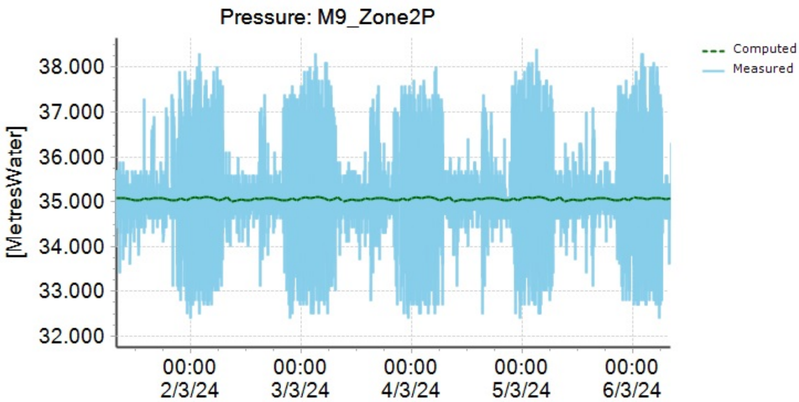


Figure 5.11. *Calibration Measurement station 9 (M9), Zone 2 pressure data*

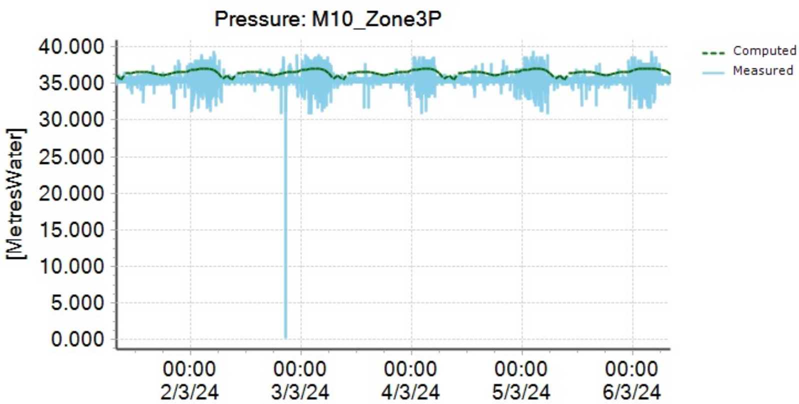


Figure 5.12. *Calibration Measurement station 10 (M10), Zone 3 pressure data*

5.3 Validation

The validation was done using the second data set (recorded in the loggers and from SCADA). In this stage, the overlapping period taken into account was from March 6 to 14. However, in the case of the data recorded by the data loggers, the starting times were 11 and 12 March. Therefore, for the logger data, only 2 days are used to compare computed and simulated values.

5.3.1 Validation Results

The validation results are presented in Figure 5.13 to Figure 5.22. The patterns in most of the figures show that some vertical lines represent a pressure drop and increased flow due to the waterworks doing some work on the networks during the 11th, 12th, and 13th of March of 2024. Overall, the computed values in all the validation stations follow the same patterns as the measured data. Therefore, no changes were made at this stage.

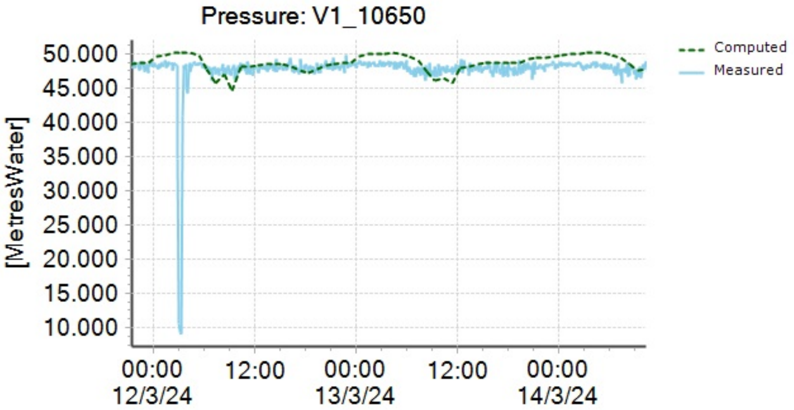


Figure 5.13. *Validation Measurement station 1 (V1), logger ID 10650*

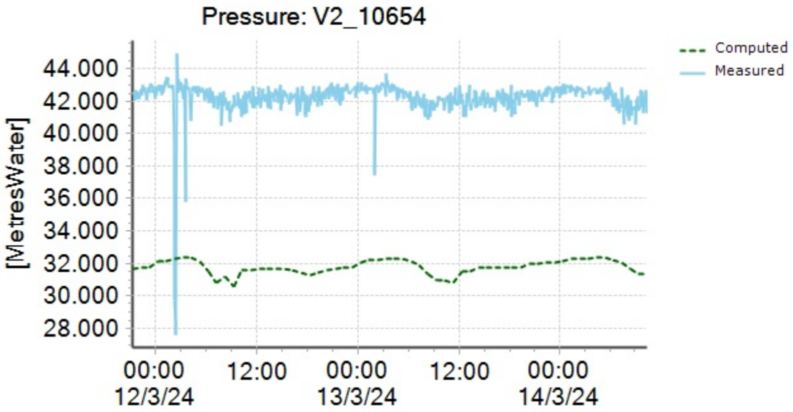


Figure 5.14. *Validation Measurement station 2 (V2), logger ID 10654*

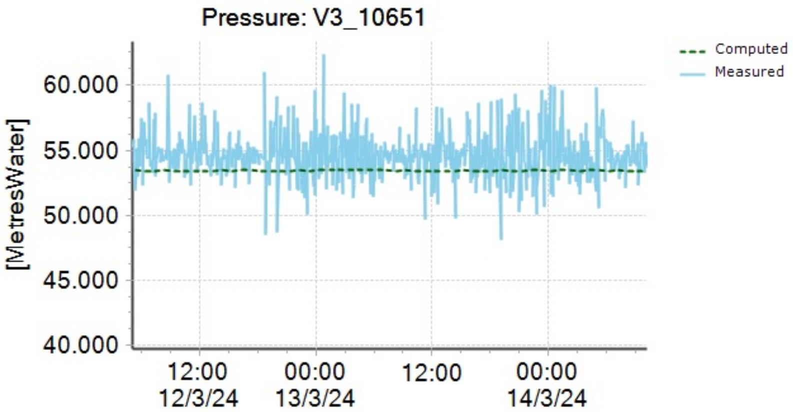


Figure 5.15. *Validation Measurement station 3 (V3), logger ID 10651*

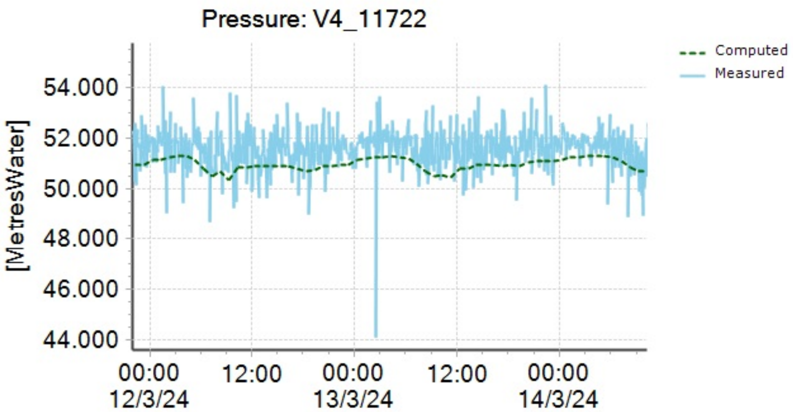


Figure 5.16. *Validation Measurement station 4 (V4), logger ID 11722*

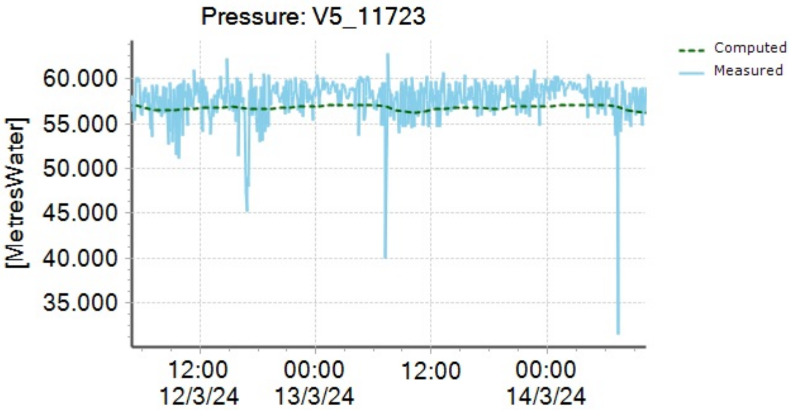


Figure 5.17. *Validation Measurement station 5 (V5), logger ID 11723*

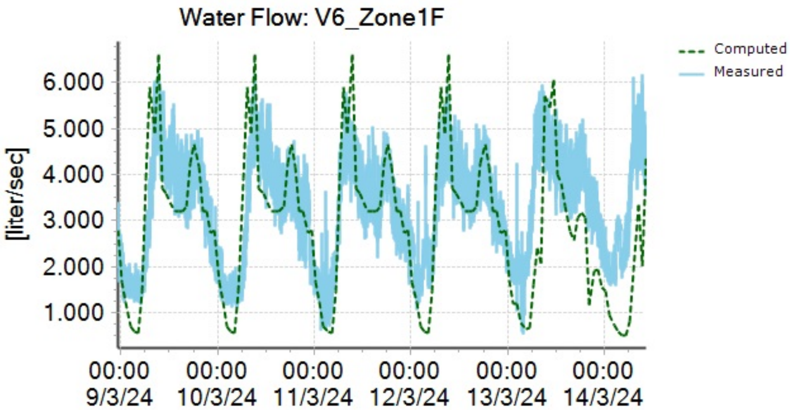


Figure 5.18. *Validation Measurement station 6 (V6), Zone 1 flow data*

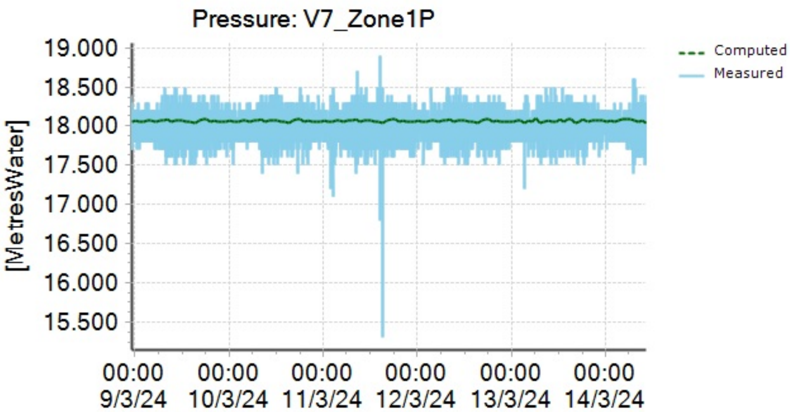


Figure 5.19. *Validation Measurement station 7 (V7), Zone 1 pressure data*

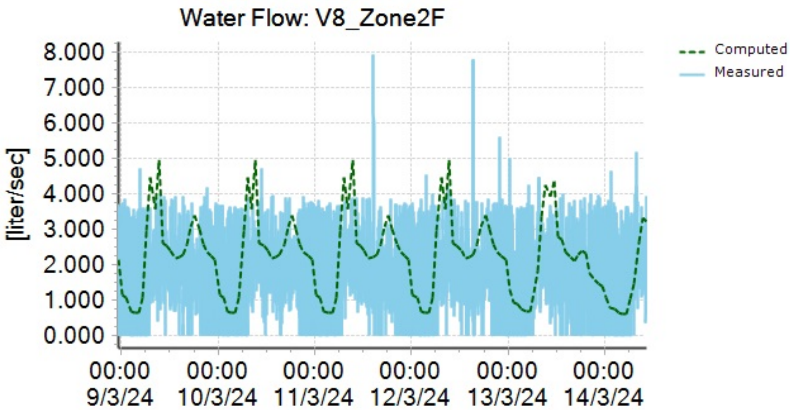


Figure 5.20. *Validation Measurement station 8 (V8), Zone 2 flow data*

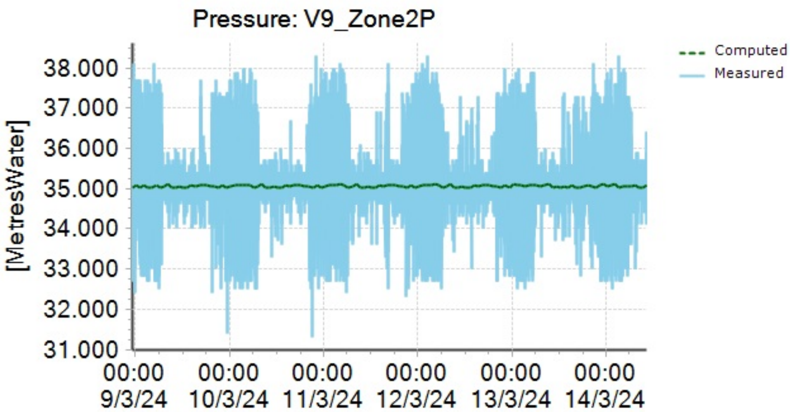


Figure 5.21. *Validation Measurement station 9 (V9), Zone 2 pressure data*

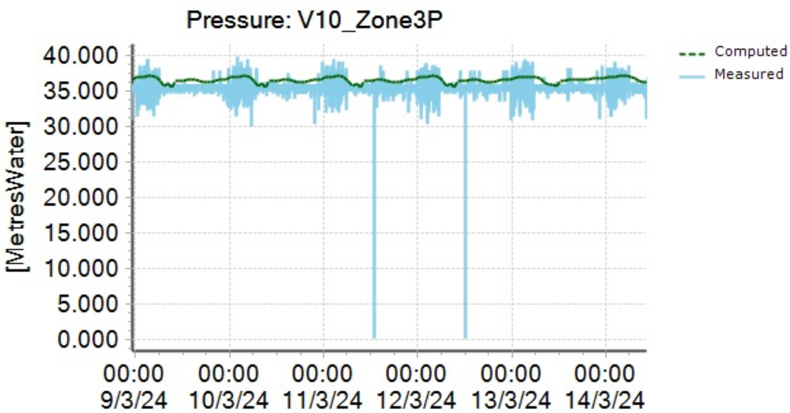


Figure 5.22. *Validation Measurement station 10 (V10), Zone 3 pressure data*

6 Model simulations results

6.1 Base model under low season conditions without leakage

The first result of the calibrated and validated model is called the Base model in this project, a simulation without leakage considerations. Figure 6.1 presents the base model results regarding maximum pressure nodes. The scale shows the nodes with pressures higher than 45 mwc with a yellow to red colour scale. The picture shows that the coastal areas (close to the sea level) have higher pressure due to the slopes of the natural terrain.

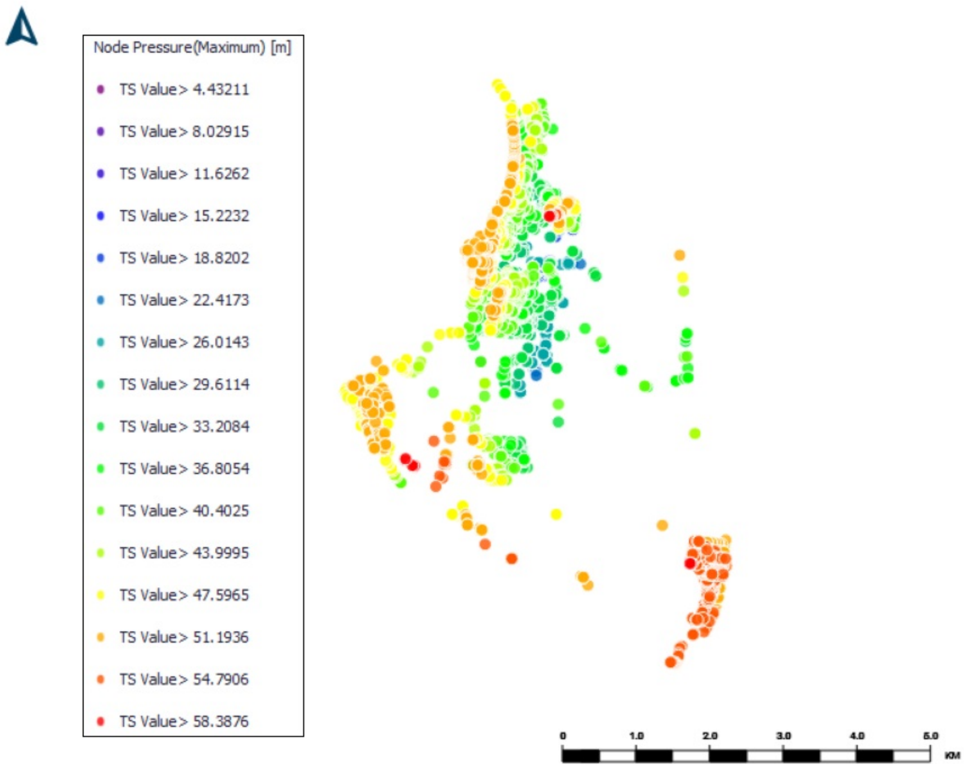


Figure 6.1. *Base model maximum pressure nodes*

The model with the demand is calibrated for low-season conditions. The

Base model results regarding pressure nodes were used as input data to simulate leakage under two scenarios.

6.2 Scenario 1: Base model implemented with leakage under low season condition

6.2.1 Zone 1 results

The results regarding the pump's daily energy consumption for Zone 1 are presented in Figure 6.2 and Figure 6.3 for pump 1 and pump 2, respectively. The average consumption for pump 1 is 1.0712 kW, with peaks reaching 1.85 kW, whereas for pump 2, the average is 1.0902 kW, with peaks rising until 1.85 kW. The maximum efficiency is 65.752 and 65.769 % for pump 1 and pump 2, respectively. The lowest efficiency is reached during the night, with 29.875 % for pump 1 and 32.042 % for pump 2. The waterworks have three pumps, but one has been inactivated in the model as it should be a backup pump.

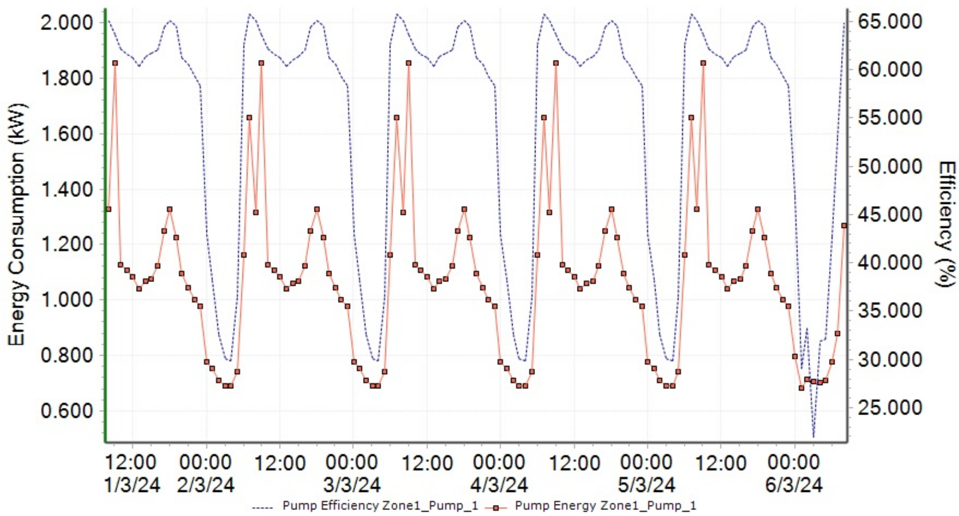


Figure 6.2. *Pump energy Vs. Pump efficiency Zone 1, Pump 1*

The cost analysis result is shown in Figure 6.4, where the daily peak is 1.594 kWh/m^3 for pump 1 and 1.486 kWh/m^3 for pump 2, these peaks take place during the night hours.

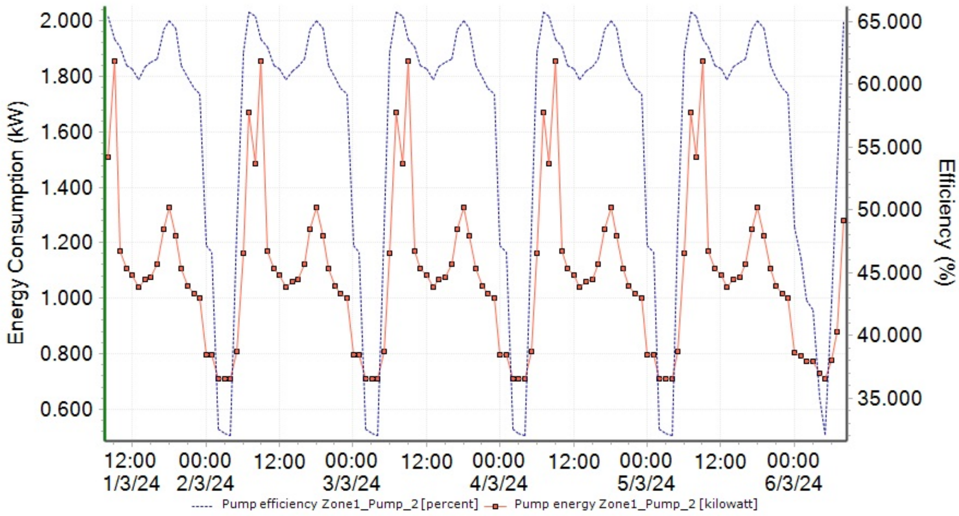


Figure 6.3. *Pump energy Vs. Pump efficiency Zone 1, Pump 2*

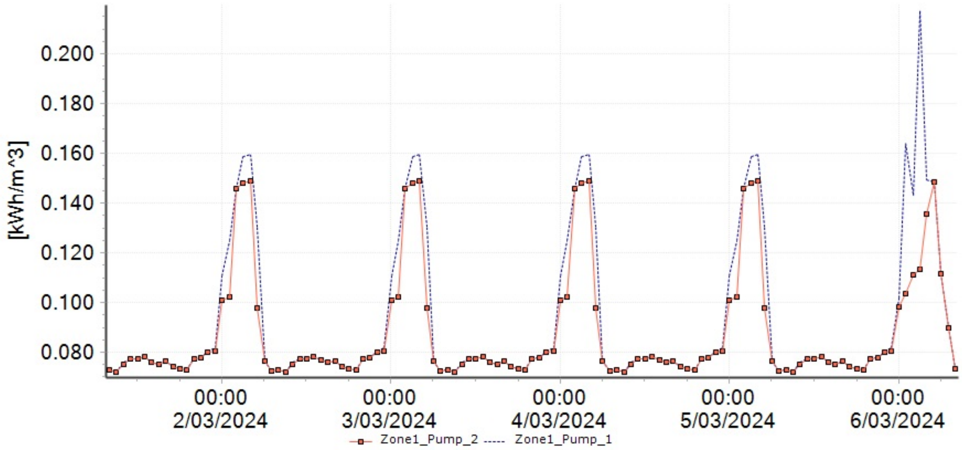


Figure 6.4. *Energy-volume Zone 1, Pump 1 and 2*

6.2.2 Zone 2 results

The simulation for Zone 2 was performed with only one active pump (Pump 1), with the other two remaining as backup. The average energy consumption is 5.6312 kW and the highest value is 6.814 kW as it is depicted in Figure 6.5. The peak efficiency is 31.426 %, whereas the lowest is 3.851 %.

The cost analysis result is shown in Figure 6.6, where the daily peak is

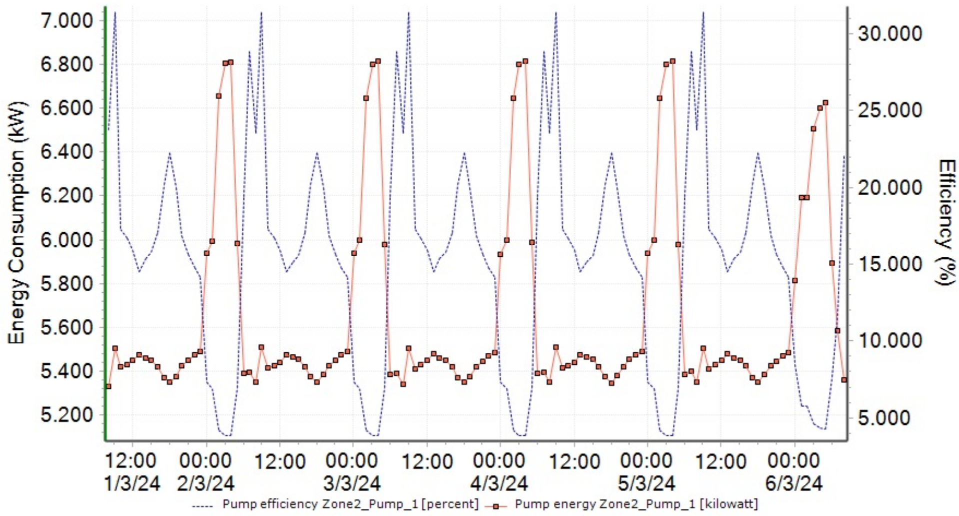


Figure 6.5. *Pump energy Vs. Pump efficiency Zone 2, Pump 1*

2.4395 kWh/m^3 for pump 1, the peaks take place during the night hours from midnight to 6 AM. However, during the day hours, the peak is 0.6359 kWh/m^3, around midday.

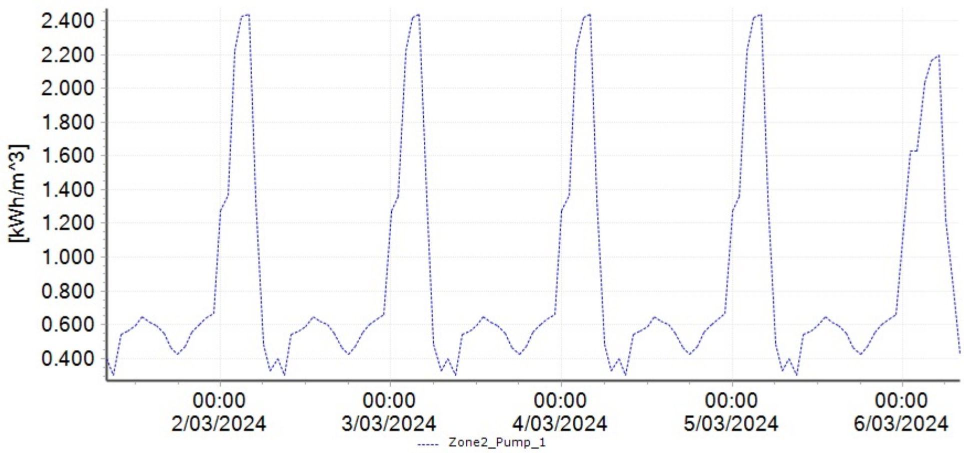


Figure 6.6. *Energy-volume Zone 2, Pump 1*

6.2.3 Zone 3 results

Zone 3 booster station has two pumps, but the simulations were carried out with only Pump 1 active and Pump 2 as a backup. The energy consumption vs the efficiency of the pump results is illustrated in Figure 6.7, where it can be seen that the average consumption for pump 1 is 0.5201 kW, with peaks reaching 0.642 kW. The maximum efficiency is 44.797 % for pump 1. The lowest efficiency is reached during the night, with 7.177 %. Figure 6.8 presents the results regarding the energy consumed per cubic meter produced. The peak at night is 1.1651 kWh/m^3 whereas the peak during the day hours is 0.4788 kWh/m^3, which occurs around noon.

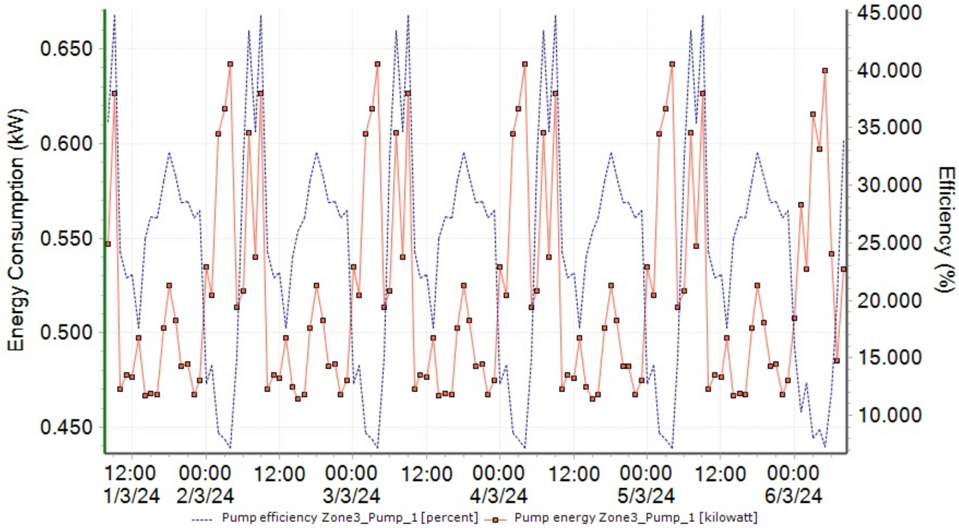


Figure 6.7. *Pump energy Vs. Pump efficiency Zone 3, Pump 1*

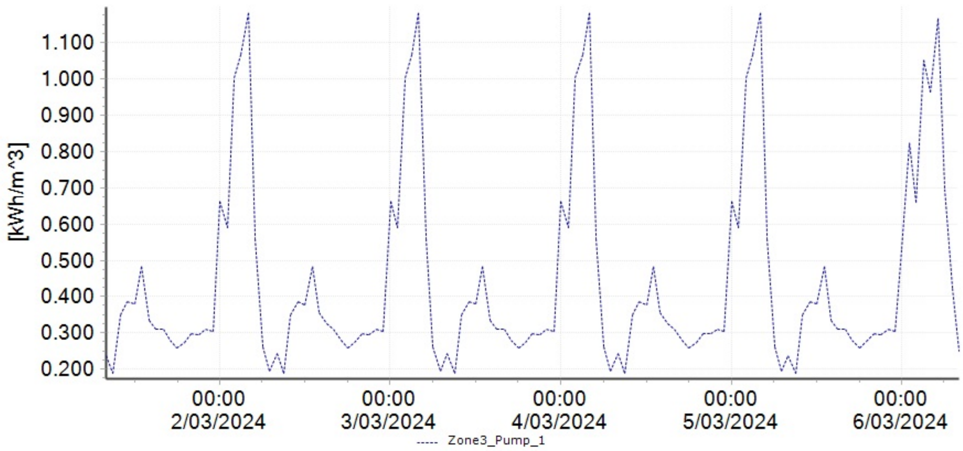


Figure 6.8. *Pump energy Vs. Pump efficiency Zone 3, Pump 1*

6.2.4 System results

In Figure 6.9, the efficiency for all the pumps simulated is presented, where Zone 1 has the highest values higher than 60 %, whereas pumps for Zone 3 and Zone 2 have low efficiencies, less than 40 %. In addition, taking into account the energy price 0.35 €-kWh (Denmark, 2024), the energy costs are presented in Figure 6.10, where the price per day is 52 € for all the pumps. This cost is only associated with the pumps' energy consumption and does not include other pumps' maintenance or operating expenses.

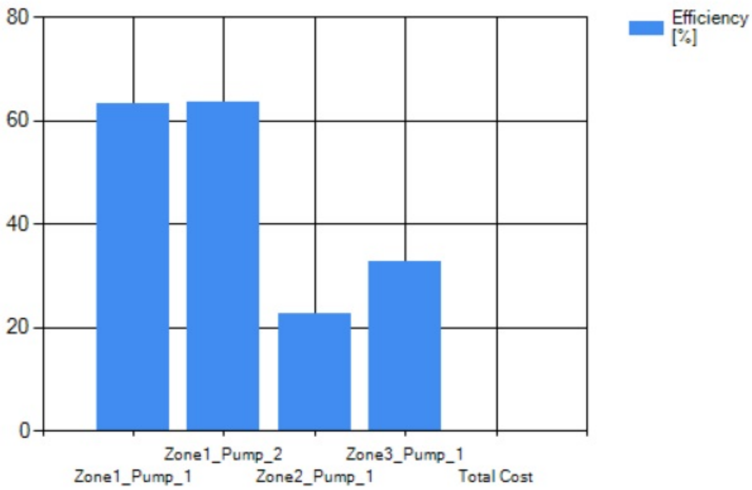


Figure 6.9. *System efficiency for scenario 1*

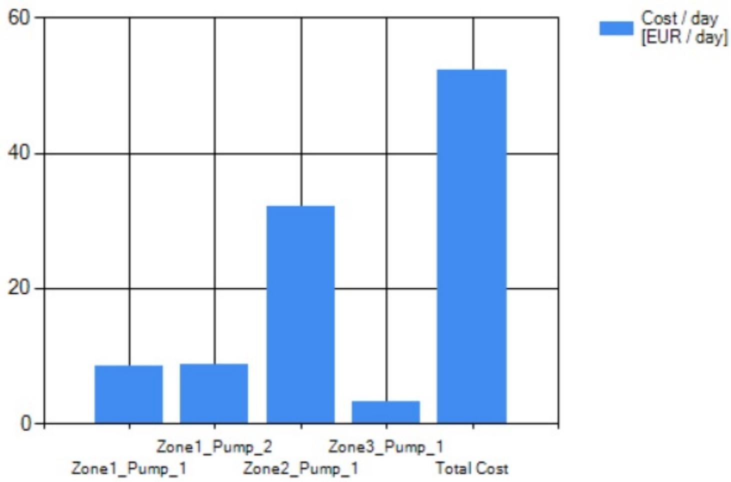


Figure 6.10. *System energy cost for scenario 1*

6.3 Scenario 2: Base model implemented with leakage under high season condition

During the high season, demand increases by 33 %. In the hydraulic model in MIKE+, this increase was made by multiplying the coefficients of multiple demands by 1.33, and the parameters regarding the leakage model were kept the same as in the base model.

6.3.1 Zone 1 results

Figure 6.11 shows the results for the energy efficiency for Zone 1 pump 1, where the minimum energy consumption is 0.6781 kW and occurs at 4 AM. In contrast, the peak is 2.7452 kW at 9 AM. Likewise, for pump 2, the minimum energy is 0.7293 kW, and the peak is also 2.7452 kW, as it is illustrated in Figure 6.12. The pump's minimum and maximum energy consumption takes place around the same hours as for Zone 1, scenario 1.

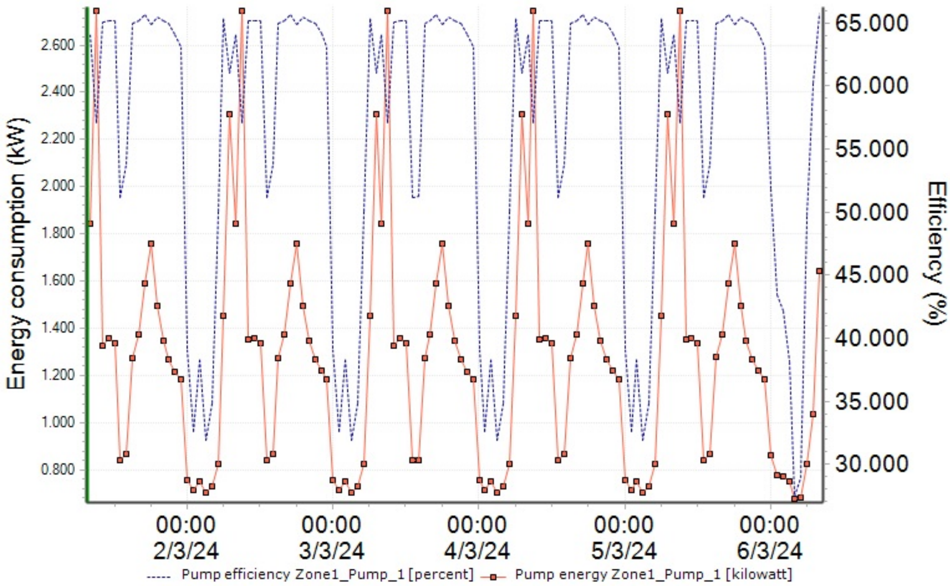


Figure 6.11. *Pump energy Vs. Pump efficiency Zone 1, Pump 1*

Regarding the efficiency for pumps 1 and 2, the peak value is reached at 8 AM, where the efficiency is 65.7537 %. In the case of the minimum efficiency, the lowest value for pumps 1 and 2 occurs at 4 AM, where the values are 27.4655 % and 34.8383 %, respectively.

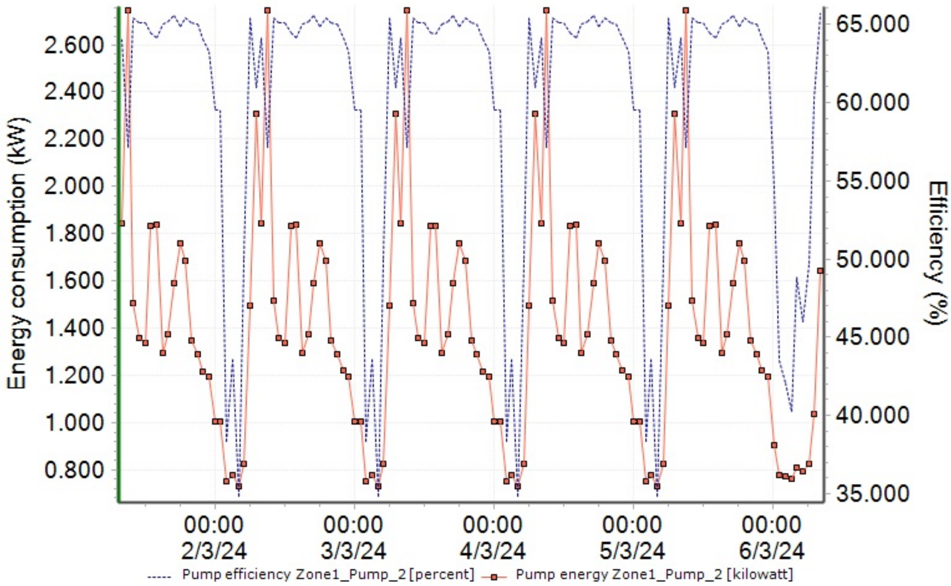


Figure 6.12. *Pump energy Vs. Pump efficiency Zone 1, Pump 2*

The cost analysis results for pump 1 and 2 are presented in Figure 6.13, where the daily peak is 0.1734 kWh/m^3 for pump 1 and 0.1367 kWh/m^3 for pump 2, these peaks take place during the morning hours.

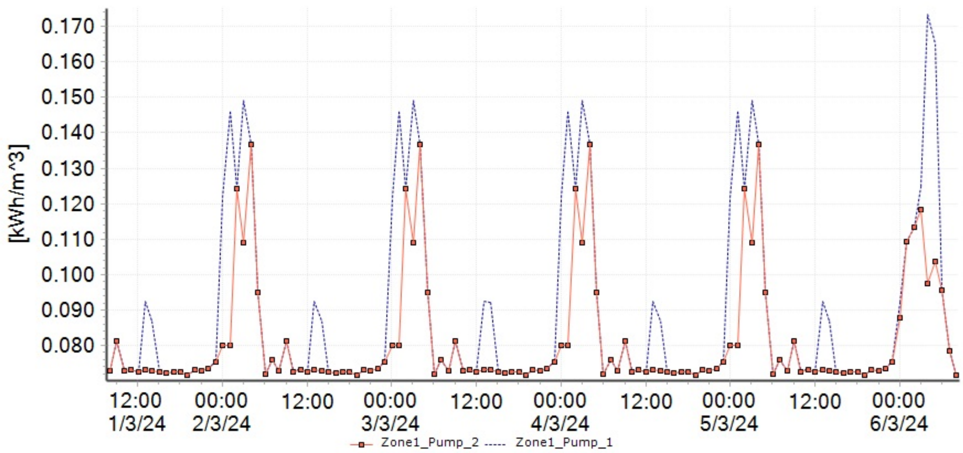


Figure 6.13. *Energy-volume Zone 1, Pump 1 and 2*

6.3.2 Zone 2 results

The average energy consumption is 5.5518 kW, the maximum is 6.3592 kW, and the minimum is 5.3120 kW as it is depicted in Figure 6.14. The peak efficiency is 39.4581 %, whereas the lowest is 5.1017 %.

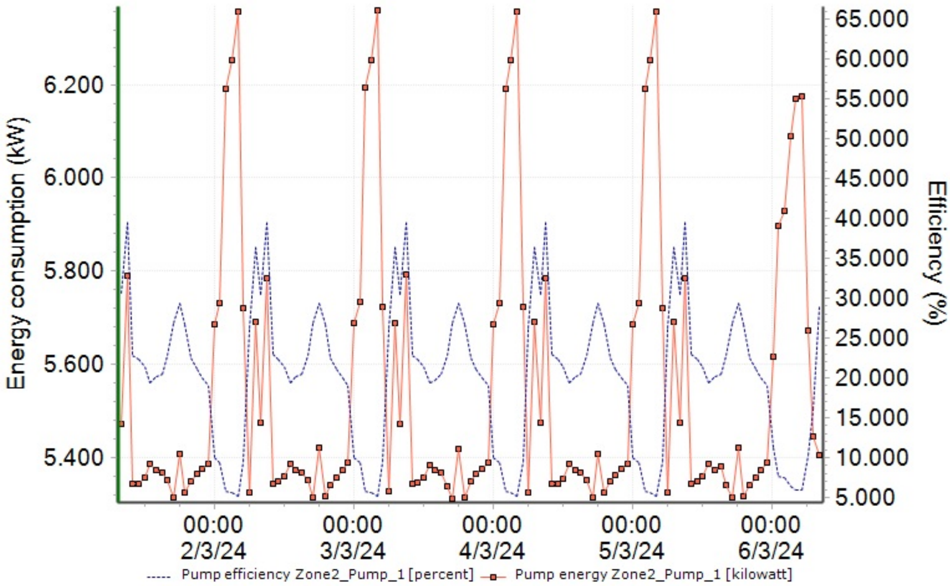


Figure 6.14. *Pump energy Vs. Pump efficiency Zone 2, Pump 1*

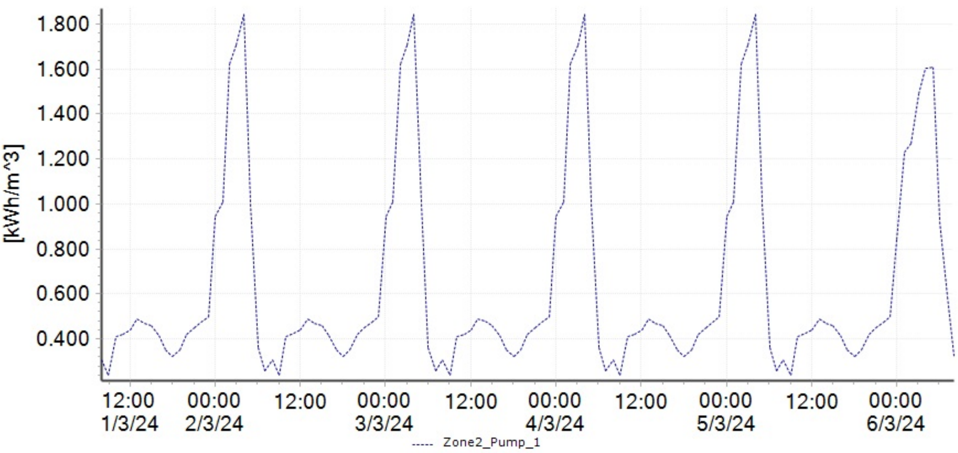


Figure 6.15. *Energy-volume Zone 2, Pump 1*

The cost analysis result is shown in Figure 6.15, where the daily peak is

1.8432 kWh/m^3 for pump 1 and the peaks take place at 4 AM. At the same time, the minimum value is reached at 9 AM with 0.2381 kWh/m^3.

6.3.3 Zone 3 results

The energy efficiency for the pumping station at Zone 3 is shown in Figure 6.16. The average energy consumption is 0.5392 kW, the highest value is 0.7091 kW, and the minimum value is 0.4658 kW. The peak efficiency is 50.6481 %, whereas the lowest is 7.0252 %. Figure 6.17 illustrates the energy volume relation where the peak reached a value of 1.2067 kWh/m^3, at 4 AM. On the other hand, the minimum value is reached at 9 AM with 0.1664 kWh/m^3.

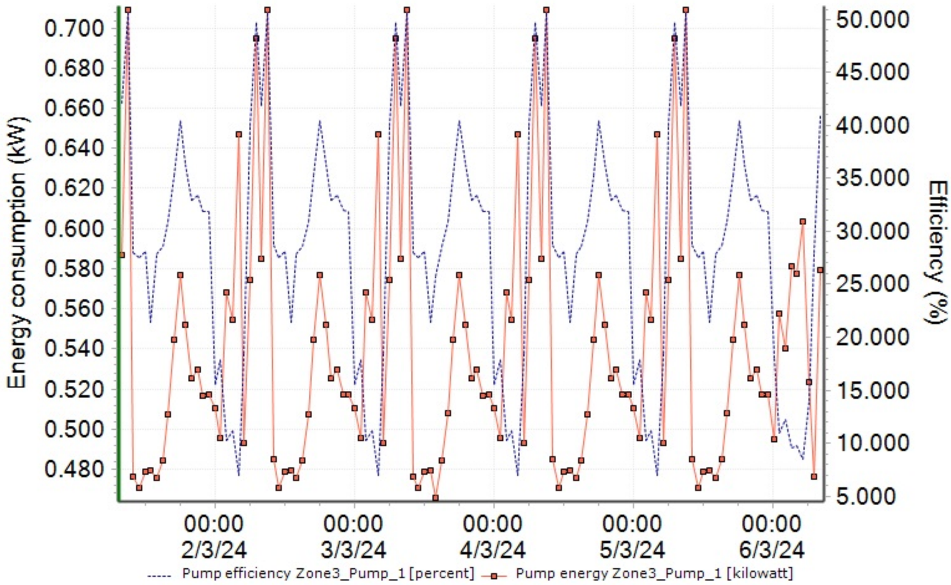


Figure 6.16. *Pump Energy Vs. Pump efficiency Zone 3, Pump 1*

6.3.4 System results

This subsection presents the results for all the pumps under Scenario 2. Figure 6.18 depicts the simulated pumps' efficiency.

Under this scenario, Zone 1 keeps the highest values (higher than 60 %). In contrast, pumps for Zone 3 and Zone 2, even when the efficiencies have increased compared to Scenario 1, still have efficiencies of less than 40 %.

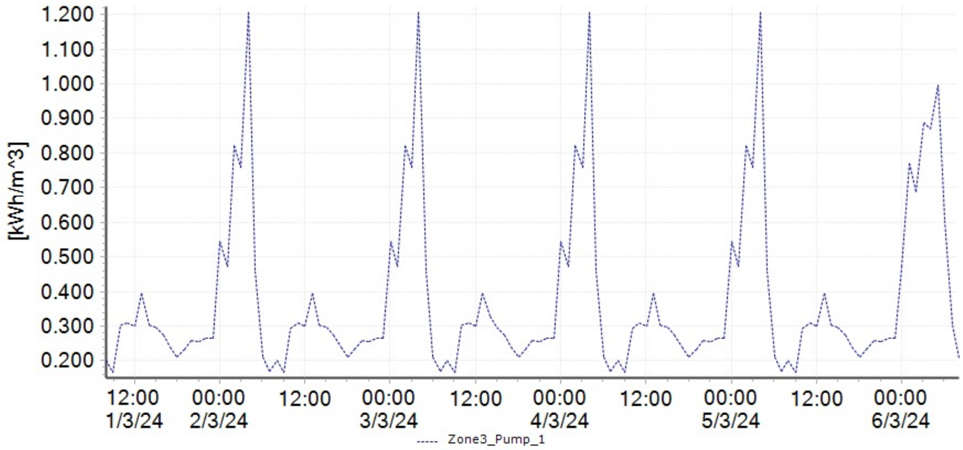


Figure 6.17. *Energy-volume Zone 3, Pump 1*

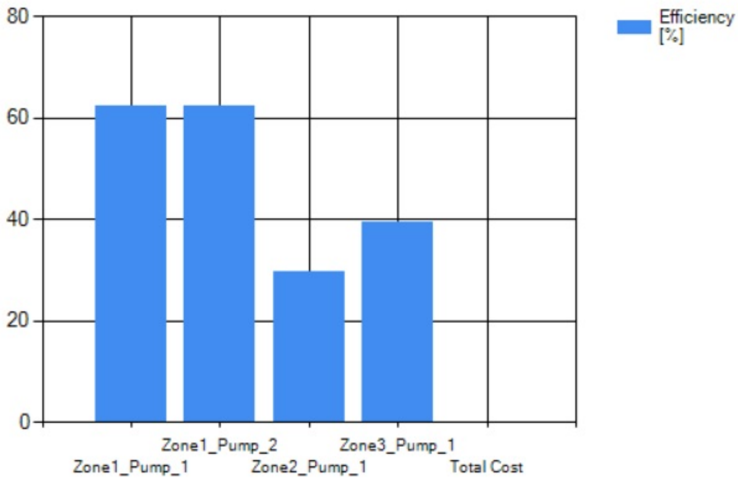


Figure 6.18. *System efficiency for scenario 2*

Figure 6.10 the energy cost is presented, where the price per day is 58 € for all the pumps.

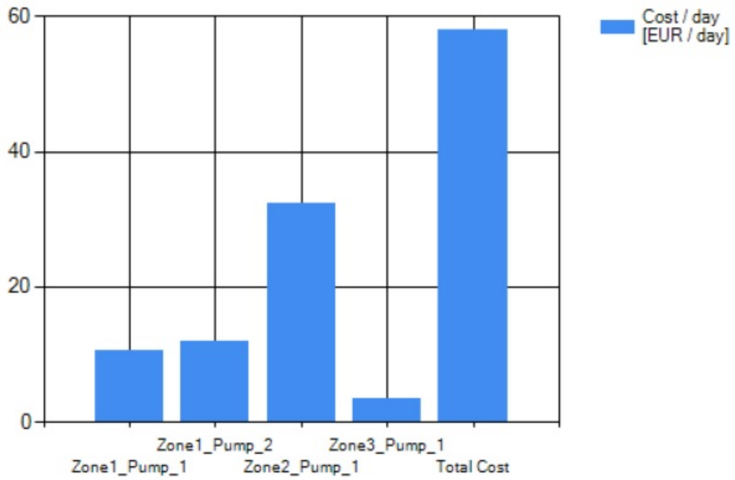


Figure 6.19. *System energy cost for scenario 2*

7 Discussions

7.1 Simulations

The energy consumption in the WDN is mainly based on the pump consumption. Although the water utility already implements energy-saving automation systems to control the pumps, it can be complex to simulate such conditions in the hydraulic model. Therefore, the model's energy consumption might be higher because it does not perform real-time energy monitoring. Thus, this factor is not analysed in this study, and the efficiencies obtained in the model are assumed. Instead, leakage and its impact during the high season have been addressed to assess energy consumption.

Based on the Energy-Efficiency plots, all pumping stations' minimum efficiency occurs during the night hours, and their maximum energy consumption occurs during the morning. This is confirmed in the plots Energy-Volume, as the cubic meter produced at night has less efficiency and increases energy consumption. Scenario 2 has a higher demand than Scenario 1, and increased cost is confirmed as more water must be pumped; this can be seen in Figures 6.10 and 6.19. Conversely, the efficiencies are increased under Scenario 2, from 23 to 30 %, for Zone 2. In the case of Zone 3, the increase is from 33 to 39 %. The efficiency is slightly increased for pumps 1 and 2 in Zone 1. These results show that it is likely that the pumps at the pumping stations for Zones 2 and 3 are not working at the appropriate operating point, and there is an imbalance because the capacity of the pumps is much greater than what is required even for high-demand conditions.

Some alternatives to consider to improve energy consumption would be installing lower-capacity pumps for Zones 2 and 3. On the other hand, due to the leaks in the network, and because these are directly related to the pressures in the network, it would be advisable to reconnect some sections for better use of the natural energy input (due to the slopes). Installing Pressure Regulating Valves (PRV) to dissipate excess pressure reduces the flow of water lost through leaks and improves the number of pipe burst events. In addition, the network renovation plan carried out by the water utility company will help improve network conditions. However, addressing the most critical areas where the pressures are too high would be recommended, as areas close to the sea level are more likely to have leakage.

7.2 Uncertainties and other issues

It is essential to highlight the uncertainties regarding the hydraulic model to consider the weaknesses and probable error sources. Different constraints were encountered during the model set-up and calibration stages. For instance, the need for more information regarding some pipe diameters was addressed through the interpolation provided by MIKE+, with 233 interpolated values. The pipe diameters are mandatory input data for the model, and the wrong assumption regarding diameters significantly alters the hydraulics in the model. In addition, some of the diameters of the pipes do not follow a conventional order in terms of the reduction of diameters downstream of the discharge pipe; the data on the plans have yet to be fully confirmed on-site. As a result, there is a backflow in areas such as Zone 3 due to the undermentioned pipes. Another input parameter that needed to be added was the pipe material; there is some steel piping around the valves found by the water utility in different maintenance works.

Although the water utility provided the open-closed valves plan, such information was not enough to run the model; assumptions regarding the area were performed, such as making Zone 1 independent from Zone 2 due to backflow coming from Zone 2, making it impossible to run the pumps in Zone 1 under such conditions. Therefore, two valves were assumed to be closed to isolate such zones.

Furthermore, the demand data used for the model correspond to the year 2022, whereas the measured data used for the calibration and validation was recorded between February and March 2024. The year difference can generate changes in the water demand, making it more difficult to calibrate a good model using old and current data. In addition, the data for calibration and validation were recorded in different periods, so the volume of available data was reduced because these must overlap simultaneously. The model does not include real-time energy optimisation, which is carried out thanks to the energy-efficient programmed drivers installed at the pumping stations. Therefore, considering the setup of genuine pumps, the results of this study could reach even higher efficiency.

Manual calibration has proven to be a valuable resource in different ways, in identifying errors in the model such as wrong pipe intersections, additional links created during the valve creation, and the performance of valve settings. Therefore, during model calibration, it is essential to start manually to identify errors in the model, and then it would be recommended to proceed using the Auto calibration provided by MIKE+. Regarding leakage modelling, it is suggested to use Genetic algorithms and machine learning, among other methodologies, to find the best emitter coefficient and exponent to get more accurate results and less time-consuming (Maskit & Ostfeld, 2014).

It is also important to mention that the area south of Ebeltoft was considered in the model. However, the water utility has no intentions of changing the area above because it was renovated two years ago and will not make any changes in the long term.

8 Conclusions

The hydraulic model in MIKE+ was successfully configured and run for the entire Egedal water distribution network. This model holds great potential for a variety of uses, such as guiding renovation plans, simulating pump changes, and facilitating network new connections. The modelling, which incorporated leaks in the water network, was a significant step in bringing the model as close to reality as possible. The location of the emitters was chosen randomly; however, this approach can be modified to provide a more precise methodology for leak identification, further enhancing the model's capabilities.

The simulations, conducted under two different scenarios, low and high season, revealed a significant issue. The pump performance in two of three stations was found to be low, indicating energy wastage. In order to optimize the energy consumption, the pumps should be resized. Particularly at night, when demands are reduced, these pumps should be replaced with others of lower capacity. This strategy would not only cover the demand but also achieve good efficiency, leading to a better Energy-Volume relationship. The system's efficiency is further enhanced during the summer months when demand increases, aligning the pump performance closer to its operating point.

While the current model represents a significant step forward, it's crucial to emphasize the need for additional research to enhance its accuracy, particularly in areas such as pump curves. This ongoing effort will ensure that the model more faithfully represents the complex dynamics of the drinking water distribution network.

Bibliography

Andersen, Hans Skifter and Mark Vacher (2009). “SOMMERHUSE I DANMARK. HVEM HAR DEM OG HVORDAN BRUGES DE?” In.

DANVA (2022). *Water in Figures*. Accessed: 31-5-2024. URL: https://www.danva.dk/media/8746/5307102_water-in-figures-2022_web.pdf.

Denmark, Statistics (2024). *Energy Prices*. Accessed: 23-5-2024. URL: https://www.dst.dk/en/Statistik/emner/miljoe-og-energi/energiforbrug-og-energipriser/energipriser.

DHI (2024). *MIKE+ Water Distribution Guide*. Accessed: 5-3-2024. URL: https://manuals.mikepoweredbydhi.help/latest/Cities/MIKE_Plus_Water_Distribution.pdf.

DjursVand (2024). *FORSYNINGSOMRÅDER*. Accessed: 1-3-2024. URL: https://www.djursvand.dk/djurs-vand#forsyning.

GRUNDFOS-a (2024). *CRE 32-2-1 A-F-A-E-HQQE*. Accessed: 23-2-2024. URL: https://product-selection.grundfos.com/products/cr-cre-cri-crie-crn-crne-crt-crte/cre/cre-32-2-1-99071942?pumpsystemid=2289495134&tab=variant-curves.

GRUNDFOS-b (2024). *CR 90-2-2 A-F-A-E-HQQE*. Accessed: 23-2-2024. URL: https://product-selection.grundfos.com/es/products/cr-cre-cri-crie-crn-crne-crt-crte/cr/cr-90-2-2-96124076?pumpsystemid=2289495750&tab=variant-specifications.

GRUNDFOS-c (2024). *CRIE 10-5 A-CA-A-E-HQQE*. Accessed: 23-2-2024. URL: https://product-selection.grundfos.com/products/cr-cre-cri-crie-crn-crne-crt-crte/crie/crie-10-5-99071462?pumpsystemid=2278387169&tab=variant-curves.

Gupta, Gagan (2017). *Monitoring water distribution network using machine learning*.

Maskit, M and A Ostfeld (2014). “Leakage calibration of water distribution networks”. In: *Procedia Engineering* 89, pp. 664–671.

Miljøstyrelsen (2005). *Miljøprojekt nr. 998*. Accessed: 6-4-2024. URL: https://www2.mst.dk/udgiv/publikationer/2005/87-7614-592-1/html/kap02.htm#2.1.

NIRAS (2008). *Landskabsforhold i Østjylland*. Accessed: 5-3-2024. URL: https://borisbrorman.dk/wp-content/uploads/2015/12/Landskabsforholdistjylland.pdf.

Puust, Raido, Zoran Kapelan, Dragan Savic and Tiit Koppel (2006). "Probabilistic leak detection in pipe networks using the SCEM-UA algorithm". In: *Water Distribution Systems Analysis Symposium 2006*, pp. 1–12.

Saghi, Hassan and Abbas Ansari Aval (2015). "Effective factors in causing leakage in water supply systems and urban water distribution networks". In: *American Journal of Civil Engineering* 3.2, p. 60.

Toolbox, The Engineering (2006). *SDR (Standard Dimension Ratio) and S Pipe Series*. Accessed: 23-2-2024. URL: https://www.engineeringtoolbox.com/sdr-standard-dimension-ratio-d_318.html.

WAVIN (2023). *VA Prisliste*. Accessed: 23-2-2024. URL: https://wavin-digital-indianajones-prod.storage.googleapis.com/assets/category/839fd0ca-25c2-4e61-8e41-eb322ca6aeb6/c9f2af27-7729-4913-ba03-4eed65c83ee7/258cfeb7-bd3e-4c83-8ebb-e8abf7f1d751.