CHALMERS
UNIVERSITY OF TECHNOLOGY

Leakage Localization through modelling
Creating a method for leak localization in plastic pipes

Master’s thesis in Drinking water

David Grönbäck

Department of Civil and Environmental Engineering
Water and Sustainability Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

MASTER’S THESIS ACEX30

Leakage Location through modelling

Creating a method for leak localization in plastic pipes

DAVID GRÖNBÄCK

Department of Civil and Environmental Engineering
Water and Sustainability Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

Leakage Localization through modelling
Creating a method for leak localization in plastic pipes

David Grönbäck

© David Grönbäck, 2020

Supervisors:

Thomas Pettersson, Department of Civil and Environmental Engineering, Water and Sustainability Technology
Andreas Hermansson, Sustainable Waste and Water, City of Gothenburg
Behroz Haidarian, Sustainable Waste and Water, City of Gothenburg
Birthe Riisnes, DHI Group
Petr Ingeduld, DHI Group

Examiner:

Thomas Pettersson, Department of Civil and Environmental Engineering, Water and Sustainability Technology

Department of Civil and Environmental Engineering
Water and Sustainability Technology
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone: +46 (0)31 - 772 1000

Cover:
Water leakage from pipe at connection with smaller pipe

Pixabay
August 11, 2015

Acknowledgements

I would first like to thank the wonderful people at DHI, Johan Spännare and Birthe Riisnes in particular for giving me the opportunity of studying the software Leak Localization. Despite not knowing the details of the software, your effort in learning it alongside me and providing invaluable assistance has made this study possible.

A great thank you to Sustainable Waste and Water, City of Gothenburg for supplying the pressure measurers and allowing the simulated leakage in your network. In particular, two individuals require honorable mentions for the support given in this study. Andreas Hermansson, thank you for your assembly of the data and the assistance in running the first few trials. Without your dedication and input, the results would be delayed months. Behroz Haidarian, thank you for helping set up the measurers and gathering the data. Your hard work gave me the groundwork and the data needed for the entire project.

The gratitude I feel towards Thomas Pettersson at Chalmers is huge. Your guidance and helpful input made the end-result much more structured and informative. Thank you for all the time you took proof-reading my thesis and the final report, making it what it is today.

Lastly, I would like to thank Petr Ingeduld at DHI for your timely assistance. When the technical difficulties with the software was about to overwhelm me, your knowledge and helpfulness helped steer the project towards the end-result published here. Despite you being on the road and having much to do, your rapid and thorough replies made a huge difference for me.

Thank you
David Grönbäck

Abstract

Maintaining and managing the drinking water supply is one of the biggest challenges in the years to come globally. Dwindling supply in some parts of the world leading to water shortages and too much untreated water in other parts puts the water supply under constant and increasing strain. When drinking water is becoming harder and harder to acquire, the management of the clean water we produce become one of the top priorities. Today, the water loss in Sweden is on average 20 %, which is higher than average compared to other countries in Europe. To reduce the water loss, several methods may be applied to locate the leakage. One such method is based on a calibrated MIKEURBAN-model and pressure measurements in the area. The company DHI created the Leak Localization software in 2016. Based on the commonly available MIKEURBAN modelling software, Leak Localization takes pressure measurements in the area and compares them to the calculated pressure from the MIKEURBAN-model. Based on this difference, the software calculates the probability of the leakage location and then generates a GIS-map to display the results.

In this project, a standardized method will be created to facilitate the usage of the software. The method will also be tested and evaluated based on the efficiency of the entire process. All parts of the method will be actively used, investigated and explained, and in most cases compared to other methods of data gathering or leakage localization on the market. A full comparison between all available leakage localization techniques are impossible due to the limited scope of this project. The focus of the comparison will therefore be on the data gathering aspect of the method created.

The results reveal several flaws but also the potential of the software. The possibility of a passive system that activates when the pressure drops and automatically locates leakage regardless of pipe material or dimension may change the approach of leakage localization. To fundamentally change established methods previously requiring a significant number of man-hours to an automated process is a significant advance. The main flaws are the difficulty of placing a significant number of pressure sensors on the drinking water network, the unrefined user interface and the lack of an automated calibration method for MIKEURBAN. Nearly all the flaws are currently being worked on, making this method of leak localization one of the most viable in the future.

Sammanfattning

Att bibehålla och sköta dricksvattentillgången är en av de största utmaningarna de närmaste åren globalt. Kraftigt minskande vattentillgång i vissa delar av världen som leder till vattenbrist och för mycket orenat vatten i andra delar gör att dricksvattentillgången är under konstant och ökande tryck. När dricksvatten blir svårare och svårare att få fram blir skötseln av det rena vatten vi producerar en av de högst prioriterade punkterna. I dagens Sverige förloras i genomsnitt 20 % av allt vatten innan det når recipienten, vilket är över det europeiska genomsnittet. För att minska vattenförlusterna kan flera metoder användas för att hitta läckaget på ledningarna.

En av dessa metoder är baserat på en kalibrerad MIKEURBAN-modell och på tryckmätningarna i det berörda området. Företaget DHI skapade Leak Localization-mjukvaran 2016. Baserat på det vitt använda modelleringsprogrammet MIKEURBAN, Leak Localization använder tryckmätningar tagna i området och jämför dessa med de beräknade tryckvärdena i MIKEURBAN-modellen. Baserat på denna skillnaden så kan mjukvaran räkna ut var den mest sannolika punkten för läckaget är och sedan generera en GIS-karta för att visa upp resultatet.

I detta projekt kommer en standardiserad metod skapas för att förenkla användandet av denna mjukvara. Metoden kommer även att testas och utvärderas baserat på effektiviteten av hela processen. Alla delar av den skapade metoden kommer aktivt att användas, utforskas och förklaras och i de flesta fall jämföras med andra metoder att samla data eller lokalisera läckage som finns på marknaden idag. En fullständig jämförelse mellan alla tillgängliga läckagelokaliseringsmetoder är omöjlig på grund av begränsningarna på detta projekt. Fokuset på jämförelsen kommer därför ligga på datainsamlingen i den skapade metoden.

Resultatet visar flertalet brister men även potentialen för mjukvaran. Möjligheten att ha ett passivt system som aktiveras när trycket faller och automatiskt lokaliserar läckaget oavsett material eller storlek på ledningen kan förändra vår syn på läckagelokalisering. Att fundamentalt ändra etablerade metoder och tekniker som tidigare krävt mycket tid och energi till en automatiserad process är ett stort steg i rätt riktning. De största bristerna är svårigheterna att placera en stor mängd tryckmätare på ett befintligt vattennätverk, den outvecklade användarvänligheten och avsaknaden av en automatisk kalibreringsmetod i MIKEURBAN. Nästan alla brister är under utveckling för tillfället, vilket gör denna metod till en av de mest lovande läckagesökningsmetoderna i framtiden.

Table of content

1. Introduction

Water is the most important resource in the world. All life depends on the availability of water. Given that 97 % of all water on earth is locked in the ocean as saltwater and 70 % of all the remaining freshwater is contained in the ice caps (UNESCO,2017). Less than 1 percent of the entire supply of freshwater is available to the world’s population today. The distribution of freshwater is also unbalanced across the globe. 6 countries contain 50 % of the world’s freshwater reserves. The annual renewable freshwater resources in the European union has been declining during the period 1990-2017 (European Environment Agency, 2019). The largest decreases were observed in southern Europe. Spain’s annual renewable freshwater resources has decreased by 65 %, Malta’s has been decreased by 54% and Cyprus 32%. The main reason is the high pressures exerted by climate change and population increases.

With the climate change showing no signs of stopping, global temperatures rising to extreme levels and severe water shortages occurring in unexpected locations, the importance the water supply is extremely high. Efficient management of the dwindling supply of water is therefore of vital importance. Today, more than 45 million cubic meters of clean water are lost per day worldwide. This translates to 14 000 000 000 $ every year, thus making reduced leakage a highly profitable question (Water Intelligence, 2019). Global water leakage control can therefore save a tremendous amount of money and water if proper control measures are used.

During the 1970s and the 1980s, mostly cast-iron pipes or copper pipes were used for the drinking water networks in Sweden (Sustainable Waste and Water, 2019). Leakage detection in cast-iron or copper are time consuming but manageable. The main method for locating the leakage is to use the sound of the leakage. Vibration transmits very well in metal pipes which can be detected by either people or equipment. By using triangulation and data collection from several listening posts, the leakage can be determined. The reparation of the leak is then very easy and does not require the excavation of the entire pipe.

In the 1990s and after, the main material changed to plastic. Plastic is resistant to corrosion, is cheap and fit the soil in Gothenburg well. The main issue with plastic is the absence of vibrations. The old, tried-and-tested methods are ineffective in plastic pipes. At the end of 2019, 32,6 % of the pipes in Gothenburg are plastic, see figure 1 (Sustainable Waste and Water, 2019), new methods must be introduced to enable efficient leakage localization. The blue line is the amount of cast iron pipes, the dotted purple line is ductile cast iron, the green line is plastic pipes and the yellow line is other material, such as copper.

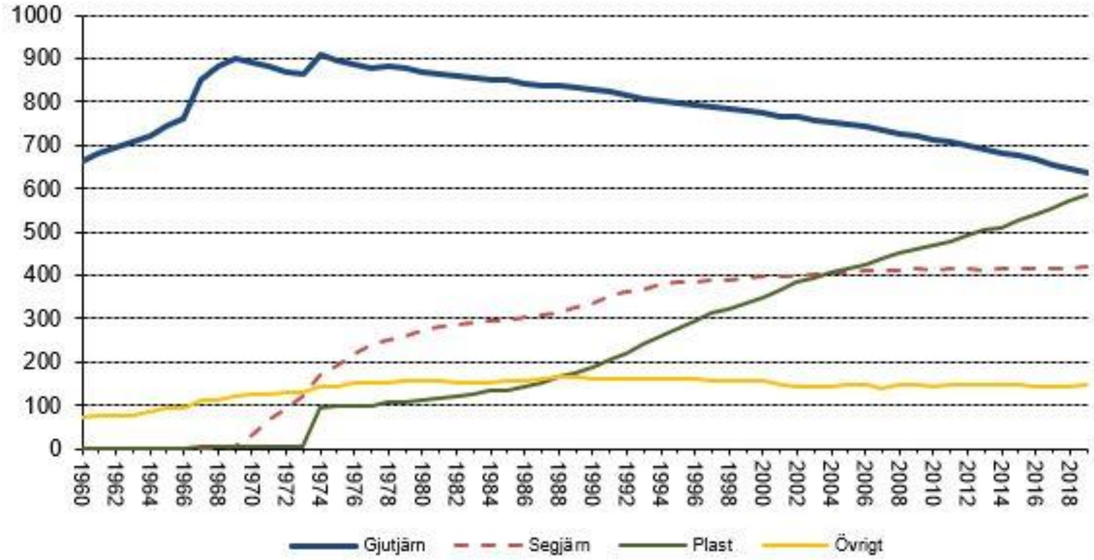


Figure 1, Amount and material of drinking water pipes in Gothenburg from 1960 to 2019

1.1 Aim

The aim is to utilize and analyze the software Leak Localization and investigate if it is capable of effectively evaluate a specific pipe network and localize simulated leakage.

The primary aim is to develop and evaluate the method of usage with the assistance of Sustainable Waste and Water and DHI to make model-based leakage localization more efficient.

The secondary aim is to develop an easy-to-use method that other municipalities could use in the future. A method that uses computer models to localize leakage instead of having to spend considerable effort for the same result.

1.2 Limitations

I. The DHI software Leak Localization will be used as presented, no effort will be used to modify it.
II. The only method in the software to be used will be the Differences method, not the Time Series method.
III. Only one small part of the Gothenburg network will be tested, no other area or municipality will be tested in this trial.
IV. The number of pressure-measuring points will be limited to five.
V. No comparison will be done with other programs or calculation methods.

1.3 Workflow

Five pressure sensors will be placed on a part of the drinking water network in Gothenburg, the network being owned and operated by Sustainable Waste and Water, City of Gothenburg chosen based on specific criteria. The pressure sensors will gather data during a full week. During the final day of the measurements, simulated leakage will be created by opening a fire hydrant to an exact outflow in three different locations on different times. These measurements enable calibrating an MIKEURBAN model of the area in question. The pressure changes recorded during the simulated leakage will be inserted into a module supplied by DHI, designed to calculate the location of the leakage. With controlled parameters in the area and in the MIKEURBAN model, the accuracy and sensitivity of this module can be estimated and the whole process analyzed based on possibility of mass usage.

2. Background

Leakage alters two main factors, flow and pressure. Currently, flow measurements are used to narrow down the search radius to a certain area, but further investigations are required to locate the exact position of the leakage. The main limitations of flow measurements are the tools required. They are both expensive to buy and expensive to install. Digging is always required and often the pipe is required to be shut down for the installation to proceed. This is highly inefficient to do just to locate certain leakage.

Pressure is much easier to measure in specific points at a specific time. The purchase cost is much lower, and the installation cost is minimal. They can even be attached to fire posts, which must be placed at least once every 50 meters in a Swedish drinking water network.

The company DHI have developed a simulation tool for accurately determining the location of leakage using pressure measurements. This tool will be used on measurements from the pipe network of Sustainable Waste and Water, City of Gothenburg. This is done to investigate the efficiency of the tool in Swedish conditions and if the efficiency is high enough, to establish this method as a solution to the plastic pipe problem.

2.1 External and internal systems

Division of leak localization techniques are broadly done in two categories, external systems and internal systems (Airull Azizi Awang et al. 2018). The external systems characterize by using external sensors attached to pipelines to capture data and generate alarms. Examples of external systems are pressure sensors, acoustic sensors, vibration sensors, Ground penetrating radar (GPR) and Distributed Temperature sensing. The data collected by the external systems are then processed by the internal systems. Amongst the internal systems are numerous techniques and methods such as classifiers, mass balancing, multi-label and residuals. Some of the most noteworthy internal systems are Mixed-model and data driven approach, multilabel classification, interval estimation and sensitivity analysis. Due to limitations, the internal systems will not be analyzed or compared. The internal system used by the Leak Localization software is a statistical classifier based on sensor pressure measurements.

2.2 Ground penetrating radar and infrared photography

GPR inspection is a geophysical figure technique, available for exploration and monitoring of subsurface pipes (Atef, A et al. 2016). The main applications are varying and covering many fields, such as engineering, geology and archeology. GPR utilizes electromagnetic waves to transmit through the ground and reflect off underground objects, see figure 2. An antenna receives the reflected waves and a profile of the objects underground is mapped. By visually inspecting this generated map, underground leakage can be found. The most suitable application of this technique is larger metallic pipes excluding the ones beneath unsuitable ground, such as pavements. GPR is considered time consuming and unable to produce the exact location of the leakage.

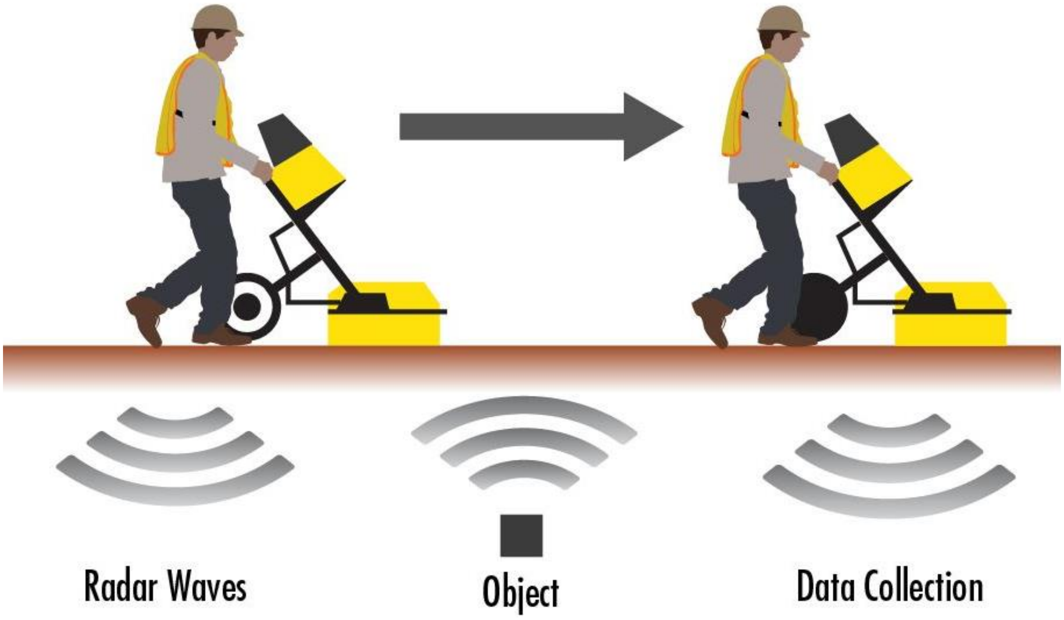


Figure 2, Simplification of GPR

IR technology uses temperature instead of electromagnetism to search for leakage. IR radiation is emitted and the thermal contrast on the surface show where leakage is located see figure 2. The IR technique is independent of pipe material type and pipe size. The main conditions that affect IR is the object temperature, weather conditions and soil and pavement surface conditions. Comparing IR to GPR shows the advantages of IR. It takes less time to investigate the same area and the possibility of detecting leaks in different conditions, such as under pavements, makes IR more effective than GPR.

Several new techniques of combining the GPR mapping and the IR mapping have emerged to acquire better results. The main problem remains however. It is time consuming and requires good soil- and surface conditions, thus making the strengths greater but the weaknesses remain.

2.3 Acoustic sensors

There are two versions of the acoustic sensor (Mergelas, B. et al. 2005). The older one involved gathering sound from the outside of the pipe by various methods, something that is impossible to do with non-metallic pipes or pipes with a diameter larger than 300 mm. The sound from the leak will not travel as far in non-metallic pipes. To accurately investigate these types of pipes, the United Kingdom's Water Research Council concluded that the sensor needs to be inserted into the pipes and locate the sound from the leakage from within. Sahara System introduced the internal acoustic sensor based on this report. The internal sensor is a microphone attached to a data cable that is inserted into the pipes. By following the flow of water, the microphone moves through the pipes and detects the noise created by leakage. Another method is to place the microphone in a ball and let it roll downstream. The Sahara Smartball system is an example of this. The strengths with the Sahara System are the precision of the results and the possibility of investigating hundreds of meters of large water pipes. Very few systems are able to precisely locate leakage on very large pipes. The negative aspects are the time consumed and the labor required to operate. The active search method works best in correlation with other methods that may minimize the search radius to reduce the number of pipes needing to be investigated.

2.4 Roughness compared to diameter change

The internal surface of any drinking water pipe is fouled by discharge from the water. Since the inside of the pipes vary heavily, two main classifications are currently in use (Kaur, K. et al. 2018). In the pipes with evenly distributed roughness, see figure 3, the build-up of discharge is evenly distributed, leading to a smoother flow of water. In the pipes with unevenly distributed roughness, see figure 4, the discharge stands out almost like stalagmites and stalactites. The water flowing through the pipes with uneven roughness will be turbulent and require more energy than the pipes with evenly distributed roughness. A significant amount of reports has been made regarding the roughness and the potential diameter change that occurs given time. Some try to generalize the roughness to estimate the average roughness based on time, speed and material. Others investigate a dual pronged method of both reducing the roughness and the pipes diameter. As stated by K. Kaur et. al. (2018), the diameter may be reduced by up to 50 % by sedimentation. When inserted into a modelling program, such as MIKEURBAN, the roughness in that case would be very high. The flow velocity in these cases would be tremendously high and the error from the modelling software will be correspondently high. The conclusion from the previous reports is that with aged pipes, the sedimentation functions more like a dimension change combined with an increase in roughness than solely an increase in roughness. To properly calibrate an MIKEURBAN model, a balance between dimension change and roughness needs to be implemented.

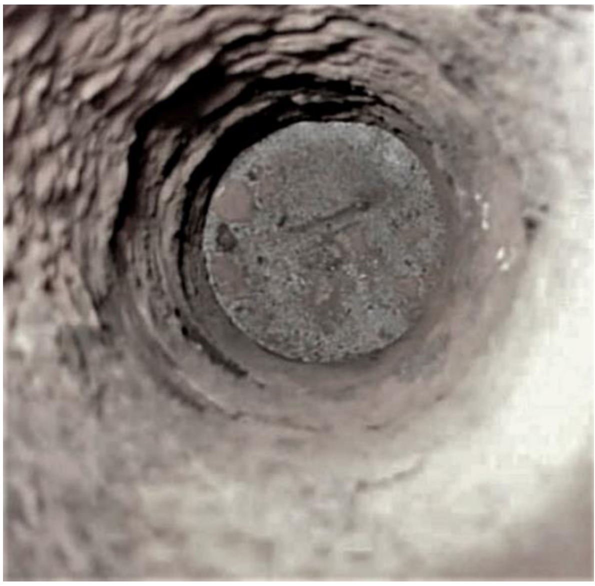


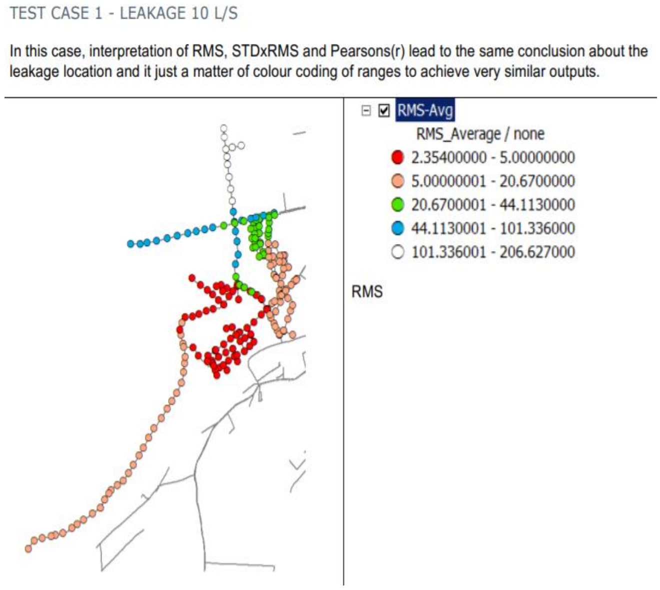
Figure 3, Even Roughness

Figure 4, Uneven Roughness

2.5 Previous trials

The previous tests of leak localization performed by DHI was located in two different countries. One was in the Czech Republic and the other in Italy. The trial in Italy was different, due to a large leakage of 25 l/s was maintained. Due to the physical limitations in the drinking water network in Gothenburg, 25 l/s is impossible to maintain for an extended period of time without damaging the pipes. The risk of accidentally creating new leakage is too great with a withdrawal of 25 l/s. The condition of the pipes in Strömmensberg laid in 1933 and 1934 is poorer than the average condition and is unable to sustain such a large withdrawal.

In the Czech Republic, a simulated leakage of 10 l/s was maintained for an entire day, and the results can be observed in figure 5, 6 and 7. Time series was used at that time, and during these trials, the Differences method will be used. For the full explanation of the differences between Time series method and differences method, see section 3.10.2. The results from the trial in the Czech Republic shows correct area of leakage but may only reduce the area needing to be further investigated. It is impossible to pinpoint the exact location of the simulated leakage. This is a significant drawback that other methods of leakage location can circumvent.


TEST CASE 1 - LEAKAGE 10 L/S

In this case, interpretation of RMS, STDxRMS and Pearsons(r) lead to the same conclusion about the leakage location and it just a matter of colour coding of ranges to achieve very similar outputs.

Figure 5,Results from a leakage localization trial in the Czech Republic, Standard Deviation calculation

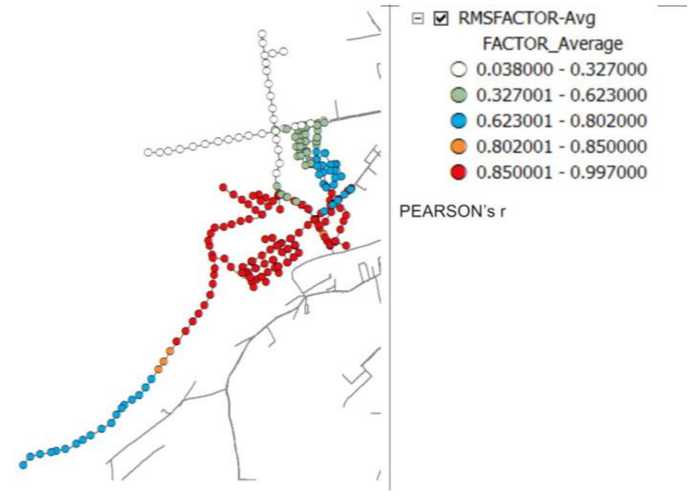


Figure 6, Results from a leakage localization trial in the Czech Republic showing the Root Mean Square Calculation

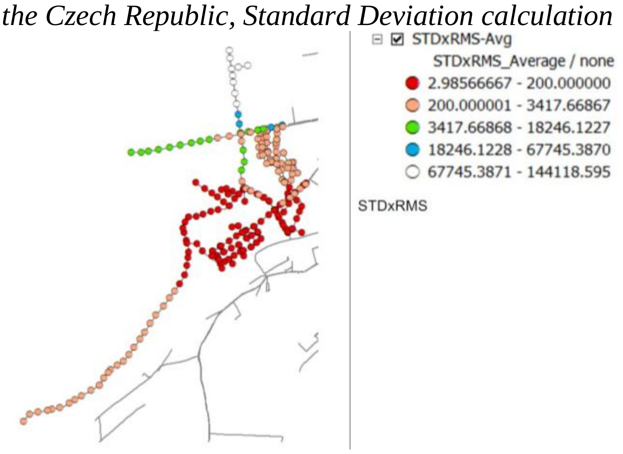


*Figure 7Results from a leakage localization trian in the Czech Republic, showing the, STD * RMS calculation*

The previous trials highlight the accuracy of the Leak Localization software during the Time Series method. The comparisons to be made with previous trials is the accuracy of the results and the distribution of values. The values in the previous trial range from 2.98 to 144 000 in the STD*RMS calculation. A low STD*RMS value indicates a low deviation between the calculated values and the measured values. For full explanation, see chapter 3.10.4.

3. Methodology

3.1 Field site description

The area chosen for the measurements, Strömmensberg, is located in the northeaster part of Gothenburg, see figure 8. With 2733 people living in the area and a pipe network of 5388m, the area is one of the smallest elevated zones in the entire network. The small size allows the 5 pressure sensors to give sufficient coverage of the area.

The measured night flow in Strömmensberg is 1,3 l/s which is 0,2 l/s lower than the theoretically calculated nightflow for 2733 consumers. This indicates that the current leakage in Strömmensberg is low enough to be negligible. The pipes are old, laid between 1939 and 1941. A few smaller pipes are laid around 1920. The roughness is estimated to be very high and the diameter is estimated to be reduced by up to 50% in all of the pipes in Strömmensberg.

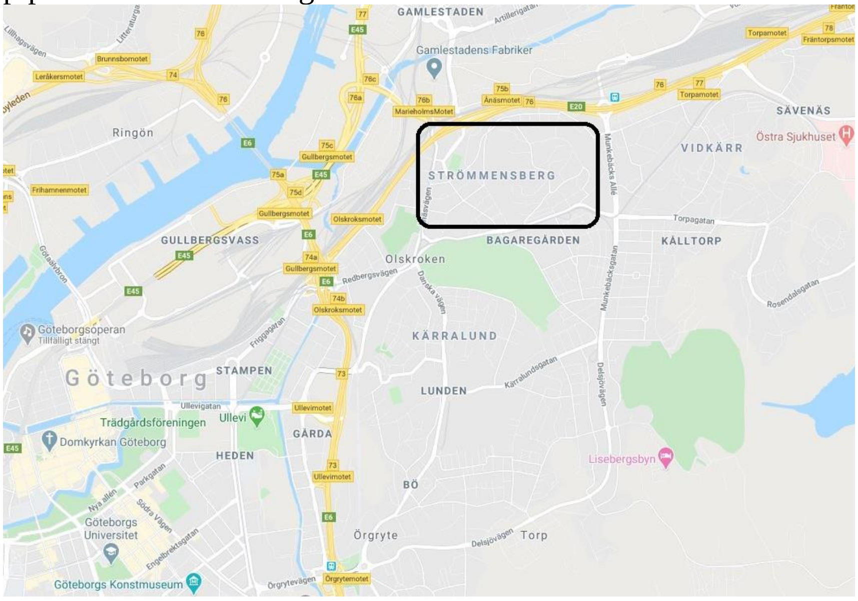


Figure 8, Strömmensberg marked in black.

3.2 Importance of factors

The conditions in each area is different. Some areas have newer pipes, and some have older pipes. Some have recent leakage detection works done, others have a low occurrence of leakage and pipe breaks. To ensure the validity of the results, these conditions and factors needs to be compared to each other when choosing the area. These factors contribute the most to the results.

- Size of area
- Age of pipes
- Similarity of pipes
- Condition of pipes
- Current Leakage
- Historical Leakage

The factor with the highest importance during this trial is the size of the area. With only 5 pressure sensors available for field measurements, a large area cannot be properly covered, which will result in large uncertainties. This factor eliminates most of the areas in Gothenburg, since most of them are large.
The second most important factor is the current leakage. With a high leakage, there will be miscalculations in the pressure drops from the simulated leakage. The study area needs to be almost completely free from leakage (have a low night flow) to ensure the correct leakage is found. In addition, if current leakage exists, the probability of making them worse is high with the added strain of the simulated leakage. With these unknowns, the entire project will be invalidated, therefore this factor is given a high importance.
The factor with the third highest importance is the condition of the pipes. This factor is closely linked to the historical leakage and the age of the pipes. If the pipes are in poor condition, the risk for additional leakage is high. If simulating a leak of 10 l/s creates a real leak, the software could miscalculate the area of the simulated leakage.

3.3 Alternative areas

Given these factors, another alternative area was considered in addition to Strömmensberg. This area was much larger, with 28 700 m of pipes providing water for 12 800 consumers. The first factor, the size of the area, was therefore inferior to Strömmensberg. The current leakage was very similar to Strömmensberg, almost non-existent. The condition of the pipes was much better than Strömmensberg. Recent pipe renewing projects in the area had much improved the area and in addition, significant leakage reducing work had recently been performed. The knowledge of this area was much better, the condition of the pipes was known to a much higher degree.
Ultimately, two factors made Strömmensberg the better choice. The historical leakage and the similarity of the pipes. Strömmensberg have a very low occurrence of leakage and the pipes are old but very similar, making it easier to calibrate the roughness and the diameter of these pipes. The alternative area had a historically high occurrence of leakage and pipe breaks in the areas that were not renewed. In addition, the pipes were very different, making the calibration of the roughness and the pipe diameter much harder. Given the larger size of the other area, Strömmensberg was ultimately the better choice.

3.4 Sensor Placement

The number of pressure sensors is limited to 5 and the location of the pressure sensors is therefore very important. Several studies of pressure sensors have been evaluated, the primary work published by Perelman et al (2016), *Sensor placement for fault location identification in water networks: A minimum test cover approach*. In the published report, a benchmark network was analysed. The size of the benchmark network was 37 500 m and the daily demand was 5 150 m^3 making the average demand 60 l/s, making it much larger than Strömmensberg. An identification score, indicating how well the number of sensors covers the area was calculated in the report, see figure 9. As can be seen, the identification score shows a diminishing return when increasing the number of sensors. The identification score is the possibility of locating an event, such as a leak in the drinking water network. In the benchmark network, sufficient coverage, over 0.9 identification score, is yielded by 7 sensors, one every 5360 m. At 10 sensors, one every 3 750 m, the identification score is 0.95. At 20 sensors, one every 1875 m, the identification score of 0.98 is very close to the maximum identification score of 0.99 reached at 48 sensors. With 5 sensors and only 5 390 m of pipes, one every 1 080 m, the identification score is close to the maximum for Strömmensberg.

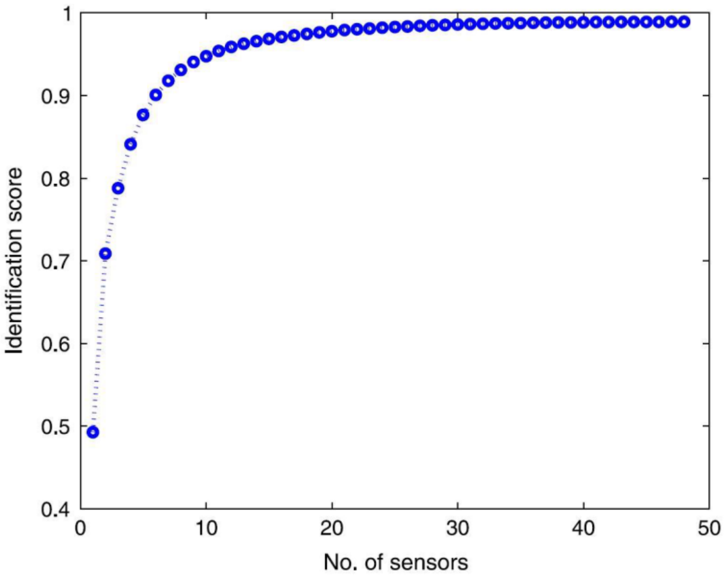


Figure 9, Diminishing return based on the number of pressure sensors (Perelman et al. 2016)

The location of the pressure sensors is of vital importance for the study performed. With the wrong nodes selected for investigation, the results will be inaccurate. Basing the location of the pressure sensors on the benchmark networks placement of pressure sensors, the exact locations of the pressure sensors can be seen in figure 10. The locations were based on the report by Perelman et al., but could not be replicated exactly due to practical issues. The pressure sensors could only be placed on fire hydrants, located with an average distance of 50 m apart.

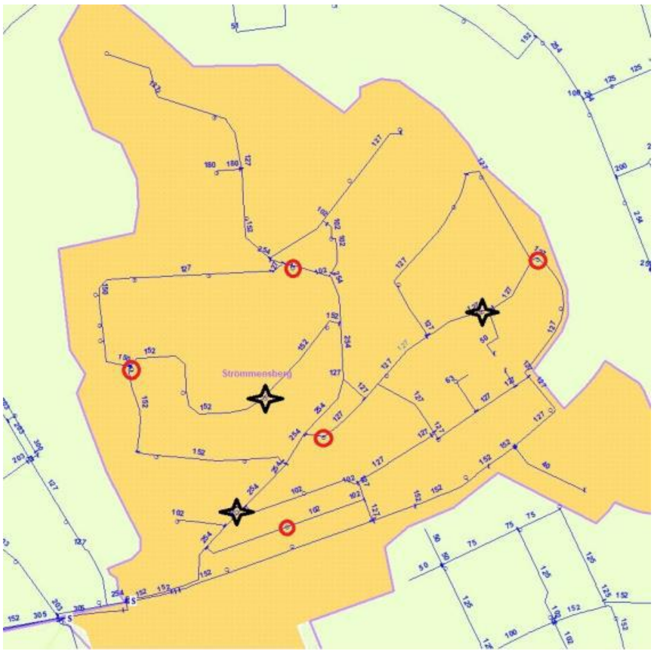


Figure 10, Red circles indicate sensor placements and black stars indicate simulated leakage

3.5 Simulated leakage

Based on previous trials and recommendations from DHI, 10 l/s were chosen as the simulated leakage. With an average inflow of around 6 l/s during peak hours, the pressure drop should be detectable and give adequate results. Based on statistics from Sustainable Waste and Water, City of Gothenburg, the average leakage in all areas that is possible to locate and repair lies between 2-10 l/s. Smaller than 2 l/s and the leak is very hard to notice and not economically feasible to repair.

Three central areas were determined to be the most fitting leakage sites based on the placement of the sensors, see figure 10. The main point of interest was the proximity to sensors to get several accurate results. All three points are surrounded by pressure sensors, giving a chance to locate the leakage from several directions. One of the points, Leakage 1, was located right on the largest feeder pipe into the area, making a capacity test possible. The capacity test takes the peak flow and adds 20 l/s to simulate the demand of the firemen when putting out a fire.

One simulated leakage was created at a time. The leakage started at 2 l/s and increased by 2 l/s every 5 minutes. This made available the investigation of how small leakage could be detected with certainty. The leakage stopped at 10 l/s, similar to a previous trial performed in the Czech Republic, see chapter 2.5.

The material used to simulate the leakage was a water hose with a sensor that measured the flow and the pressure of the water. The pressure sensor was deemed to be unstable and the measurements from the pressure sensor was more of a control method to ascertain the flow from the simulated leak. The flow sensor was analogue but recently controlled, thus validating the accuracy. In coordination with the measurements of the inflow to the area, the measurements were deemed to be accurate and in accordance with what was recorded.

Using a very advanced pressure sensor, capable of detecting water hammers, the data collection capacity was regarded to be sufficient. Giving a pressure measurement every minute, the amount of data received from the pressure sensors was large. Initially, 10 pressure sensors were initially promised but only 5 were available for use during the measurements.

The pressure sensors were installed a week in advance. The data collected from previous days showed very few irregularities and allowed the mapping and calibration of the area.

3.6 MIKEURBAN setup and calibration

With the placement of the sensors well analysed and set up, measurements were extracted in the area Strömmensberg. The tests were performed successfully, and a great deal of data was extracted. This data was inserted into the modelling program MIKE URBAN, powered by DHI. In this program, all drinking water pipes in Gothenburg are included in this model, which is also continuously updated . The main issue with the model is that the roughness value, the K-value in the pipes, is not sufficiently calibrated for this study. To make the model results, mainly the pressure calculation, harmonise with the measured pressure, the K-value (often in mm size) need to be estimated and adjusted. In old pipes where e.g. corrosion made the cross section are of the pipes diminished substantially, the K-value can be order of magnitudes higher (up to several cm) to match real pressure loss in the pipes. Another approach is to estimate a new, smaller cross-section area for the old corroded pipes and include these in the model, making the K-value more normal.

The roughness in drinking water networks depend on several factors, such as time, flow and quality of water.

The approximated value in MIKEURBAN from Sustainable Waste and Water, City of Gothenburg is that the roughness is 30 mm and that the diameter has shrunk by 5 mm. In very old pipes, the roughness is so severe that the most efficient way of calculating the flow is to decrease the diameter rather than to increase roughness. To estimate a decrease in diameter is more like the present situation than to utilize an unrealistic large roughness value. At first, an automated process for roughness calibration was searched for, but no such process was readily available to the involved parties. Therefore, an iterative process was implemented. By analysing and comparing the sensor measurements before and during the simulated leakage, the roughness and change in diameter could be approximated and evaluated.

The real-world measurements were regarded as correct due to the precise sensors used and utilized as a point of reference. Two different days were used for the calibration, the day before the simulated leakage and the day the leakage was simulated. Only measurements between 12.00 and 13.00 were used to calibrate the model. If all simulated leakage was incorporated into the model calibration, the DHI module would read back our own values to us. Therefore, two simulated leakages were deliberately left out of the model calibration to be independent from any calibration or tampering.

It is impossible to perfectly replicate the real-world situation in the pipes, therefore measurements from the day before the simulated leakage was used as a reference. The average values should be between the two days but as close as possible to the day of the measurements.

The pressure measurements from the pressure sensors (P_R) minus the pressure from the model simulations (P_M) squared and added together and divided by the number of entries gave the average difference between the pressure sensors and the model simulations, R(x), see equation 1

$$R(x) = \frac{\sum(P_R - P_M)^2}{n}$$

Equation 1, The error R(x) is the average difference, in square, between the pressure sensors (PR) and the model simulations (PM). n is the number of points used in the calculation.

The Leak Localization software, developed by DHI, bases the three methods of calculation on an MIKEURBAN model and measured pressure values, see chapter 3.10.4 for full explanation. It is therefore of utmost importance to have a model that accurately simulates the existing conditions in the Water Distribution System. In order to create a framework, current data from Sustainable Waste and Water, City of Gothenburg was utilized to set up demand curves during the hours of the day. Given the large amount of data available, these demand curves can accurately predict the average demand per minute in all the hours of the day. Naturally, not all values will be the same during all the days. Holidays and weekends vary the most, due to the number of users increasing. The highest demand is a few hours just before new-year’s eve. To bypass this inherent volatility, the measurements were set up during an entire week, to give the statistical basis of the demand curve. Data collected proved that the demand curve between two weekdays varied very little. The most stable time were between 9 and 14, when most users are at work or at school see figure 11. The blue line is for weekdays and the orange line is for weekends. The trials were as mentioned between 9 to 11 and 12 to 13

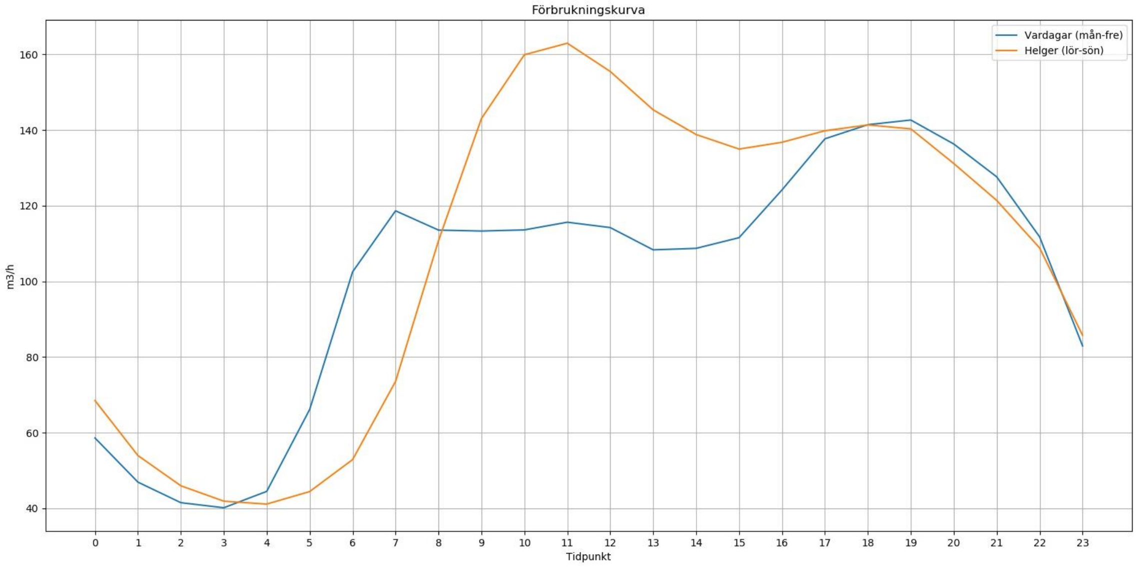


Figure 11, Demand curve during weekdays (blue) and weekends (orange)

With the demand curve in place, all the other necessary data were inserted, such as estimated pipe diameter, roughness and leakage. The background leakage, the existing leakage, were measured by the night flow in the zone, when the demand is the lowest. The demand during nighttime are based on statistics and set to 33 l per 1000 persons per minute, which yields 1,5 l/s for Strömmensberg. The measured night flow in Strömmensberg is 1,3 l/s, indicating that the leakage in this zone is negligible.

The model setup based of the modelled values and the measurements carried out by the City of Gothenburg was very accurate in some parts but in a few parts, was not as accurate as the Leak Localization software needed it to be. The main issues were the roughness, pipe diameter and simulated leakage. As discussed earlier, the roughness and pipe diameter will change over time, due to fouling inside the pipes. To create the optimal model, the individual pipes needed to be optimized based on both diameter and roughness. The simulated leakage had fewer uncertainties and were easier to calibrate. At first, the values recorded in the field documentation were used. These were not accurate and did not simulate the actual situation in the pipes. The inflow into the area were then observed and the change between the demand pattern and the actual values gave a close to perfect value of the actual output from the simulated leakage. Closer than that is impossible to reach without several pieces of specialized equipment, such as more flow sensors, installed in the direct vicinity of the simulated leakage.

3.7 The iterative process

To properly calibrate the roughness and the pipe diameter every single pipe needs to be individually examined and evaluated. Without the proper software, this would take a very long time to perform and several simplifications needed to be made. The first simplification was the creating of groups based of characteristics of the pipes. Similar diameter at the start, similar amount of water transported and similar water speed lead to relatively similar roughness and current diameter.

3.7.1 Division of area into subgroups

The largest and most important of the pipes were divided into two separate groups, 300 Cast Iron, CI and 254 CI, see figure 12. The light blue pipes are the pipes with the stated diameter. These pipes are the main distributors of water to the entire zone. The group 300 is homogenous, without any pipes branching out, making the flow more laminar. On the other hand, 254 is filled with junctions and the flow at the start of the group, the southernmost part, is higher than at the end of the group, the northernmost part. Given that the pipes are designed to not allow high water speeds, the roughness should also be relatively similar.

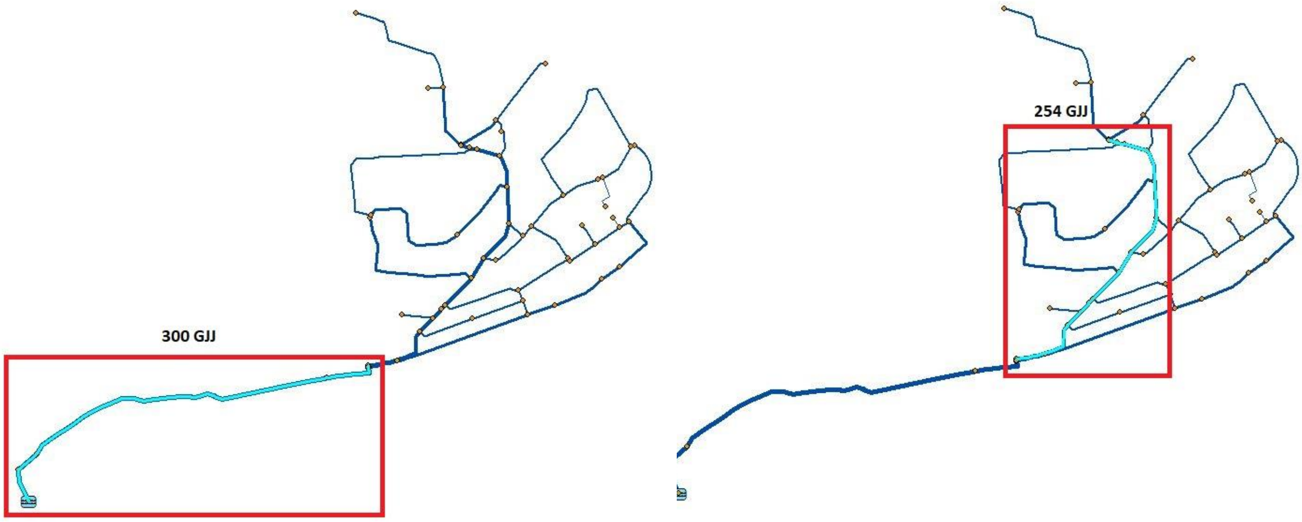


Figure 12, Subgrouping of pipes with the outer diameter of 300 mm and 254 mm, material Cast Iron.

The smaller pipes were grouped into three groups, with two of these that are very similar, see figure 13. The difference between these different groups is very small and would normally consist of one large group instead of two small. The geographical layout and the location of the measurements made these two groups better kept separate, to ensure more precise results. In addition, the iterative process made these two groups necessary.

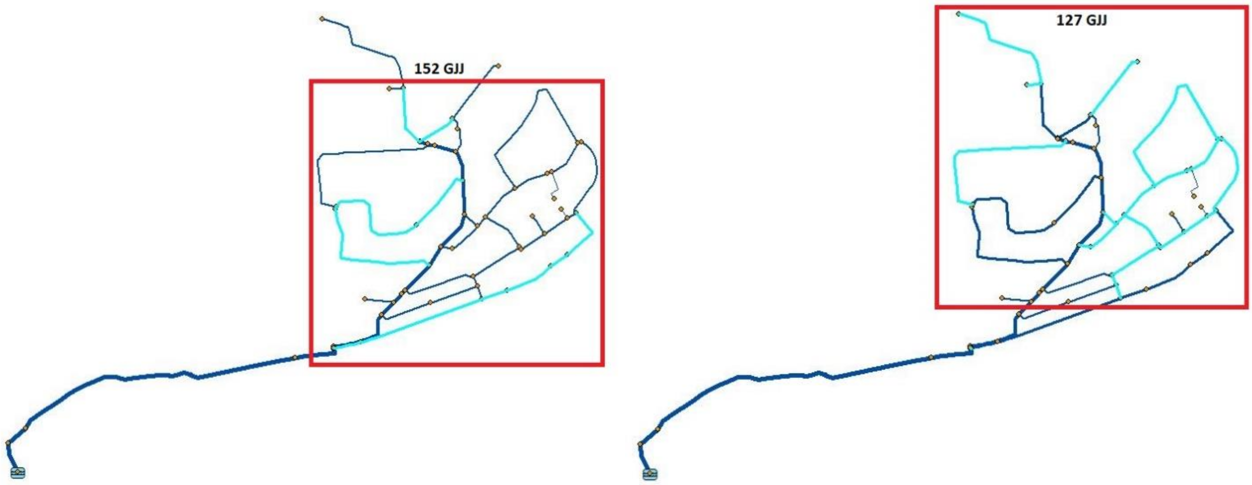


Figure 13, Subgrouping of pipes with the outer diameter of 152 mm and 127 mm, material Cast Iron.

The final group is the smallest of the pipes, 102 mm, see figure 14. These differ from other groups by the lower speed and lower flow. Due to the measurements of Blåhammarsgatan being located on one of these pipes, the roughness and diameter could be determined to a high degree. The close distance to the first and largest simulated leakage made these pipes a very important component in the calibration process. The smaller pipes outside of the marked area were regarded as negatable due to their small size and distance from points of interest.

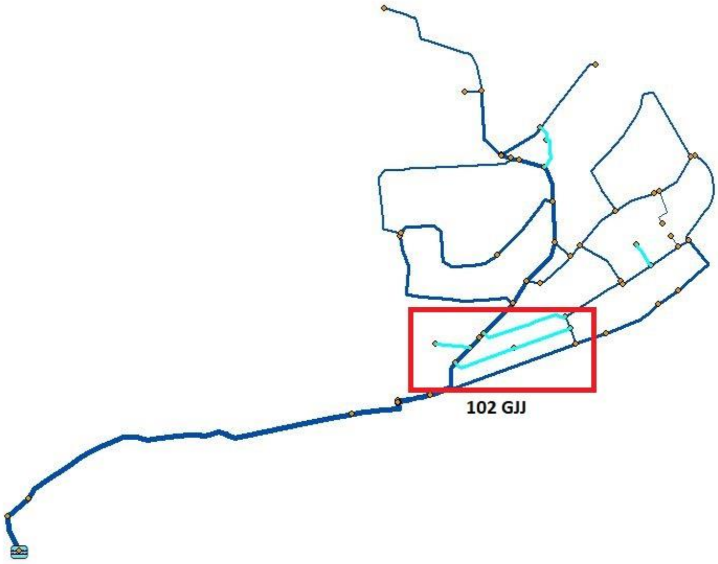


Figure 14, Subgrouping of pipes with the outer diameter of 102 mm, material Cast Iron.

3.8 Iterative process:

A step-by-step approach was selected for the roughness and diameter calibration, originating in the southern part of Strömmensberg. The third simulated leakage (Uttag 3), see figure 15 were used to calibrate the largest pipes, the groups 300 CI and 254 CI. As described earlier, the goal was to calibrate the model to be as close as possible to the measured values during the simulated leakage. At first, the inner diameter was set by using the current estimates of Sustainable Waste and Water, City of Gothenburg. The two groups with the largest pipes were calibrated first until the point Sofiagatan and Kobergsgatan were as close as possible to the measured values. After that, the grouping with 152 CI was used to get a precise value at the point Storhöjdsgatan. Finally, the smallest pipes were calibrated to get precise values for the points Blåhammarsgatan and Vidkärrsgatan. Two more iterations of this were made and final values were reached. The values are correct over large areas of pipes but are not sufficiently precise for exact calibration. These were:

- 300 CI was set to 200 mm in inner diameter
- 254 CI was set to 180 mm in inner diameter
- 152 CI was set to 95 mm in inner diameter
- 127 CI was set to 75 mm in inner diameter
- 102 CI was set to 60 mm in inner diameter

The roughness of all groups was set to 3 mm due to similar age of pipes.

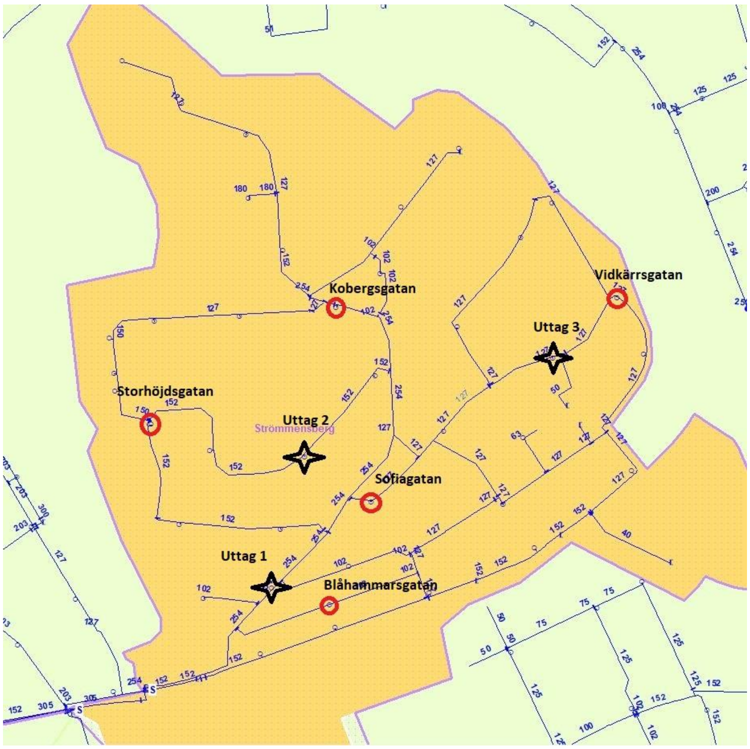


Figure 15, Distribution of pressure sensors (rings) and simulated leakage (stars)

As a trial, the roughness was set to 20-30, to verify the statement of the necessity of a dimension change. With a larger diameter and a higher roughness, the iteration process was unable to reduce the difference between measured values without the simualted leakage and the values from the model. The importance of keeping down the roughness and decreasing the diameter were confirmed by these trials.

3.9 Removal of outliers

Outliers are errors or other data that can’t be reasonably explained. These sets of data might impede or distort the statistical analysis, making the investigation invalid. The absence of strict statistical rules to identify outliers forces guidelines and statistical tests to be implemented. The empirical rule, also known as the three standard deviation rule, will form the basis for the removal of outliers in this analysis (Grafarend, E. 2006). The three-sigma rule removes the outliers by taking the median value and increasing or decreasing it by three standard deviations. This will include 99.7% of all results and at the same time removing the extreme outliers, thus ensuring the validity of the statistical analysis.

3.10 DHI Leak Localization software

In the center of the analysis lies the Leak Localization software. Created by DHI in 2016, the software is effectively an add-on calculation module to the existing hydro-dynamic flow model MIKE URBAN. Combining amongst others the MIKEURBAN and SWMM calculating engine, MIKE URBAN also includes GIS-integration. MIKE URBAN is currently evolving with the last release of MIKE 2020 in November 2019. The next step of evolution is the MIKE URBAN +, boasting a complete overview of the urban infrastructure. Based on this reliable and constantly updating program, Leak Localization has potential to grow and expand.

With the basis in the MIKEURBAN calculation engine, the Leak Localization tool allows for leakage detecting in addition to the normal hydraulic and water quality simulations. The requirements for this program to fully function is a calibrated MIKEURBAN model of the area where the leak appeared, the approximate size of the leakage and the new pressure in the area. By comparing the new pressures and the old pressures, the module can in theory pinpoint the nearest MIKEURBAN node to the leakage.

3.10.1 Technical usage of Leak Localization

In addition to the software Leak Localization, several main files are needed and will shortly be described here. The *Observed_SoloP.csv* file, the *Nodes_selection.csv* file and the text file, with exactly the same name to the *.inp* file saved from MIKEURBAN. The *.inp* file is an input data file containing all the information from MIKEURBAN. If the .inp file is named Leakage_1, the .txt file should also be named Leakage_1.
The Observed_soloP.csv file contains the pressure and at what time of the day the calculations should be performed on. For example, the first leakage reached 10 l/s at 9.58. The time in the .csv file should then be 10.00. If set to the exact time when the pressure reached 10 l/s, the pressure might vary slightly. Some time is always needed for the pressure to stabilize. The pressure in the .csv file is the difference between the measured values in the pressure sensors and the pressure in the model, without any leakage inserted. The reason no leakage is inserted in this part is because the Leak Localization will do the simulations with leakage. If leakage was to be inserted at this stage, the leakage would then be used two times, one time here and one time in the Leak Localization software.
The Nodes_selection.csv file contains the name of all the nodes to be tested in the Leak Localization software. This file is extracted from the MIKEURBAN-model.
The .txt file contains very important information. It is this file that contains the location of the two .csv files. If these files are not located properly, the Leak Localization software will not run. The observed, the minimum and the maximum leakage is also inserted here. If any uncertainties exist in regards to the leakage, here is where that uncertainty is compensated for. At the end of the .txt file, the Time Series or the Differences method is chosen. Time Series method is inserted by using the number 1 and Differences is inserted by using the number 2.
The .inp file is the MIKEURBAN-model of the area, calibrated and running smoothly. Without a fully functioning model to be based upon, nothing else will work.
When the Leak Localization has run, another .csv file is created with the results. This results file can then be expanded from a single column into several columns and inserted into a GIS-system. The GIS system will then display the results and point out the points most likely to contain the leakage.

3.10.2 Differences and Time Series mode

The two methods of finding leakage in Leak Localization is the Differences method and the Time series method. Simplified, the Time series calculate absolute values of pressures recorded by sensors during the simulated period, such as 1 day. The Differences calculates the pressure drop per sensors observed at a specific hour (or other time level).

The main difference, except the measuring time, is the comparison of pressure values at separate time levels. The Time series does not compare values at the same exact time level but instead compares observed and simulated data within a certain timespan around the respective time level. After the comparison, a compensation for possible tome shifts are done. As figure 16 shows, a discrepancy between the observed and the simulated values does not alter the result in the Time Series method. Various interpolation techniques are used based on the value of a time span. Observed and simulated time series do not need to have the same number of levels. The main role is played by the sampling frequency and the model-reporting step should always be set to the same or similar as in the telemetry.

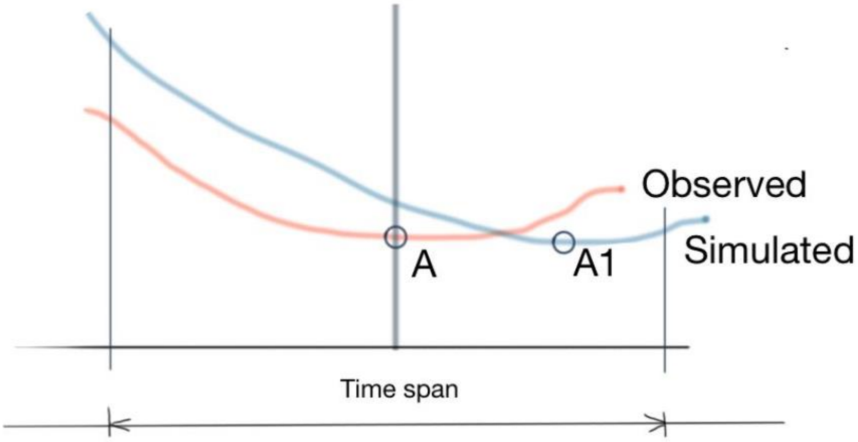


Figure 16, Time difference between observed and simulated values.

3.10.3 Requirements of usage

Several parts need to be provided for this software to be used. Pressure measurements needs to be installed before the leak occurs, to properly assess the pressure changes in the area. This is a severe limitation due to the sensitivity of pressure sensors today. To measure the pressure, a membrane needs to be in contact with the water. This membrane is particularly sensitive to water hammers and therefore can’t be maintained for long periods of time. If this were to change, the possibility of large-scale usage for Leak Localization would open up.

The proper calibration of an MIKEURBAN model is also a requirement. It is possible to calibrate the model based on pressure measurements, however these will have to be taken on a great many points in the system for a precise calibration to be possible. If other methods of determining the roughness and diameter change become available, then this could be done automatically. With higher automatization of both pressure measurements and roughness calibration, the requirements of usage become easier to fulfill.

In the best-case scenario, pressure sensors are installed in combination with flow sensors in all the houses. Determining flow is already done to calculate how much water is used by the building. Adding pressure measurements would ensure that the pressure is not too high or too low. Both situations are unwanted for a water supplier.

3.10.4 Interpolation techniques

The purpose of the module Leak Localization is to compare real measured data with simulated values from an MIKEURBAN model. Based on these two variables, three calculations are performed to specify the most likely location(s) for the leakage. The module can be set to start when flow sensors detect a leak. The module then takes the pressure measurements after the leak is simulated and compares them to a calibrated MIKEURBAN model of the area. The module then enters the leakage into every node and compares the pressure changes to the real-world measurements. When the difference between the calculated pressure values and the measured values are low, there is a high probability of the leakage being on or very near the node. Three different sizes of leakage are tested by the Leak Localization software. The range of these three values are set in the software beforehand and are used if the outflow of the leakage is uncertain. The minimum value is the lowest possible outflow and the maximum value is the highest possible outflow from the leakage. The central value is the most probable outflow from the leakage. Given the combined accuracy of the flow sensors, the central value is the verified outflow from the leakage. In the simulated leakage, 10 l/s was verified to be the outflow and therefore the verified central value will yield the most accurate result. The lowest calculated leakage was set to 8 l/s and the highest calculated leakage was set to 12 l/s but were only kept as a reference. In further studies, these values might be important. During this trial, the most important value is the central value of 10 l/s.

Three methods of calculation are performed by the module Leak Localization, Root Mean Square (RMS), Standard Deviation (STD) and the two combined, RMS*STD.

Root Mean Square (RMS)

The first calculation performed by the Leak Localization software is the Root Mean Square (RMS), see equation 2.

$$RMS = \sum_{i=1}^{n}(x_i - y_i)^2$$

Equation 2, Root Mean Square

In equation 2, x is the pressure values from the measurements and y is the pressure values from the MIKEURBAN model with simulated leakage for every node. Where RMS is the lowest, the probability of the location of the leakage is highest. More results can be found in chapter 4.1.

Standard deviation (STD) of RMS

The second calculation performed by the Leak Localization software is the Standard Deviation of RMS, see equation 3. The standard deviation is the average difference between the mean values and the actual values (in square). A high standard deviation signifies a high spread, a great variation in the values.

Definition: STD = $\frac{\sqrt{\sum_{i=1}^{n}(RMS_i - \overline{\overline{RMS}})}^2}{\overline{\overline{RMS}}}$, where $\overline{\overline{RMS}} = \frac{\sum_{i=1}^{n} RMS_i}{n}$

Equation 3, Standard deviation

As can be seen in equation 3, the standard deviation is calculated by taking the sum of the square of RMS for a certain point reduced by the average RMS. The root of this sum is then further divided by the average RMS. This gives a clear number to the deviation of the RMS of the point to the average RMS. More results can be found in chapter 4.2.

RMS x STD

By taking the RMS and multiplying it with the STD, a certain level of accuracy can be gained. A low RMS value signifies that the MIKEURBAN model finds no great difference between the measured values and the model values which include the leakage (Ingeduld, P. 2016). A low standard deviation reveals that the variation of RMS for the chosen point is very low. When multiplied together, the combination of two good values are highlighted, rather than a single value being high. A single value may contain errors or anomalies, two values in combination is very rarely the result of an error.

4. Results

Measurements on site and off site, in the pumping station supplying water to the area, confirms the size of the simulated leakage. The most accurate calculations should therefore be the ones with the correct leakage size, 10 l/s, not the other calculations of Leak Localization, see chapter 3.9.4. Only these calculations will be analyzed in the results part. For full calculations, see Appendix 1.
In addition, the second simulated leakage is kept as a reference, not as the final results. As mentioned in chapter 3.4, the second and third leakage, was first and foremost used as a means of calibrating the MIKEURBAN-model. The first simulated leakage was only used to test the Leak Localization software and should be regarded as the main result.

4.1 Root Mean Square

The first calculation performed by Leak Localization is the Root Mean Square, RMS. The simulated leakage of 10l/s, marked on figure 17, gave an average pressure drop in the pressure sensors of 2,43m. As figure 15 shows, several areas marked in red are regarded as the most probable sites for the leakage. The point where the leakage was extracted are marked in dark orange, only one step away from the red color that indicates the most probable site of the leakage. The point of the leakage is very close to another point, also marked in dark orange, indicating that the area in question is homogenous and close to being the most probable location. Only one other point is marked in dark orange and it is far from any orange point, making this point less likely to contain the leakage. Two points are marked by the software as the most probable locations, one being close to the extracted leakage and the other one some distance away. The point away from the real leakage is close to a bright green point. Green indicates that there is a large difference between the measured pressure values from the pressure sensors and the pressure calculated by the MIKEURBAN model. Red indicates a small difference between the measured pressure values and the calculated values. For full equations, see chapter 3.10.4.

As can be seen in figure 17, several factors points to the correct area. One of the two red points are in the correct area, only one point removed from the correct point and two out of three dark orange points are in the immediate vicinity, one being the correct point.
Two points, one red and one dark orange indicate the wrong area. The red point is the location of the pressure sensor Storhöjdsgatan.

The second simulated leakage of 10 l/s, marked on figure 18 caused an average pressure drop of 1.85m, which is significantly lower than the first leakage. The map generated by the second simualted leakage shows that the Leak Localization software deems the point that actually contain the leakage to have a low probability of containing the leakage. The most probable points to contain the leakage is located several nodes away, located on the largest pipes in the area. The most probable point of the second simulated leakage is very close to the most probable point of the first simulated leakage.

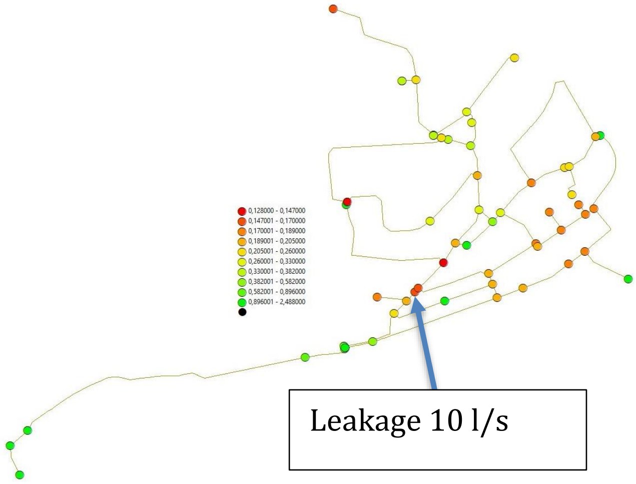


Figure 17, Root Mean Square, first point of leakage

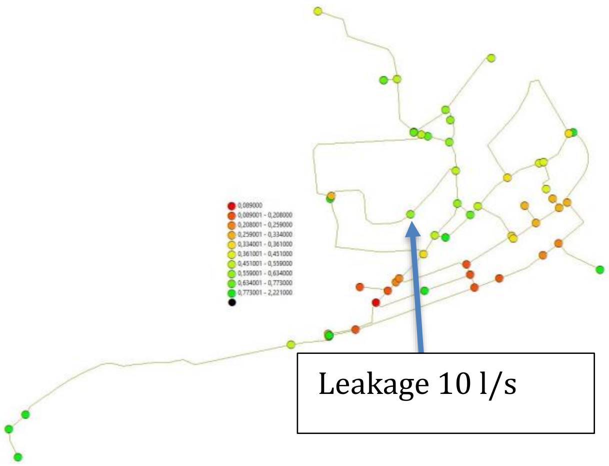


Figure 18, Root Mean Square, second point of leakage

A low value of RMS signifies that the measured values from the pressure sensors and the calculated values from the MIKEURBAN-model are similar. The points that are most probable to contain the leakage are the points that responds most like the real-world measurements when a leak of 10 l/s is inserted. A high value of RMS signifies that the MIKEURBAN-point does not respond like the real-world measurements when a leak of 10 l/s is inserted.

4.2 Standard Deviation

The second method of calculation in the Leak Localization software is the Standard Deviation, STD. Identical data as the RMS calculation are used, the only difference is the method of calculation. Figure 19 shows the results from this calculation with the first simulated leakage. Out of the four points most likely to contain the leakage, two are in the immediate vicinity of the point containing the leakage, one of the two being the point of the simulated leakage. Two other red points are marked as the most probable location for the leakage. One of these points are the point containing the pressure sensor Storhöjdsgatan and the other one is the node furthest to the north in the area. The point to the north only has green points surrounding it, meaning the points surrounding the red point are not likely to contain the leakage. The red point where the pressure sensor Storhöjdsgatan is located is surrounded by yellow points.

One point could mean a statistical error, two points close together are much more likely to contain the leakage. Since the points surrounding the two red nodes apart from the simulated leakage are all unlikely to contain the leakage, the most likely area to contain the leakage is the area surrounding the simulated leakage. In addition, the Standard Deviation calculation determines the two points marked in black to be statistical outliers. With the mean value of 0.155, and the standard deviation of 0.11, two points are removed due to the results exceeds the mean value plus three times the standard deviation, see chapter 3.9 for full equation.

The second simulated leakage shows even more uncertainties during the STD calculation than the RMS one, see Figure 20. The points most likely to contain the leakage is the ones directly on top the largest pipes to the southwest of the area. The point where the leakage was simulated is not regarded as one of the most probable leakage sites by the STD calculation, just like the RMS calculation. The difference between the RMS and the STD calculation is the difference between the first and the second leakage. The RMS of the first and second leakage results are similar in regards to the location of the most probable location, not in their accuracy. The STD calculations shows no such similarities in location of probable leakage. As with the RMS though, the first simulated leakage is fairly accurate and the second is not accurate.

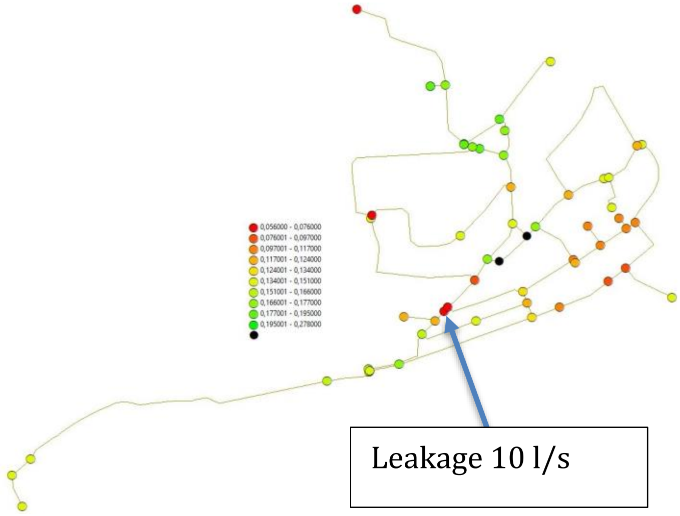


Figure 19, Standard Deviation, first point of leakage

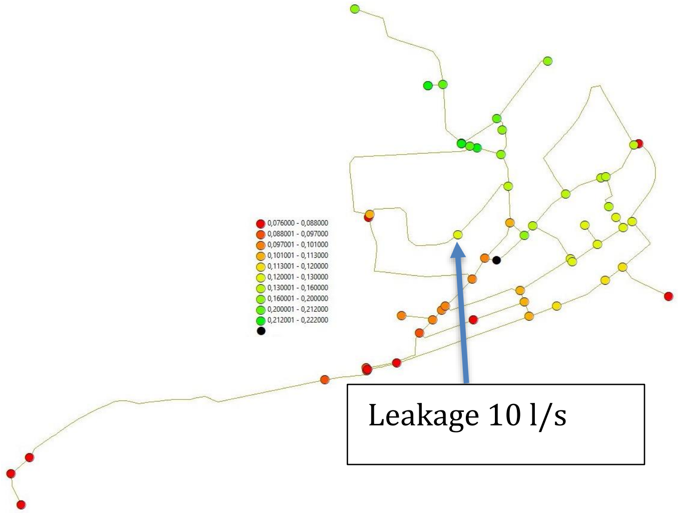


Figure 20, Standard Deviation, second point of leakage

A low value of STD signifies that the Root Mean Square value of the point is very close to the average Root Mean Square. A high value signifies that the RMS value of the point is not close to the average RMS. This value determines the distribution of values in the area. The ones closest to the average RMS will be the ones most probable to contain the leakage.

4.3 RMS * STD

The final method of calculation is the two methods combined. The lowest value of RMS * STD is the point with both a low RMS and a low STD value. As can be seen in figure 21, of the four points most likely to contain the leakage, three points close to each other and one being the site for the leakage. The high number of outliers can be explained with the method of calculation. Since high values multiplied by high values becomes exponentially higher than low values multiplied by low values, the amount of statistical outliers also becomes much higher.

If the RMS calculations were inprecise and the STD calculations were also pointing in the wrong direction, the RMS * STD calculations are bound to be inaccurate. As can be seen in figure 22, the most likely points to contain the leakage is far removed from the actual leakage.

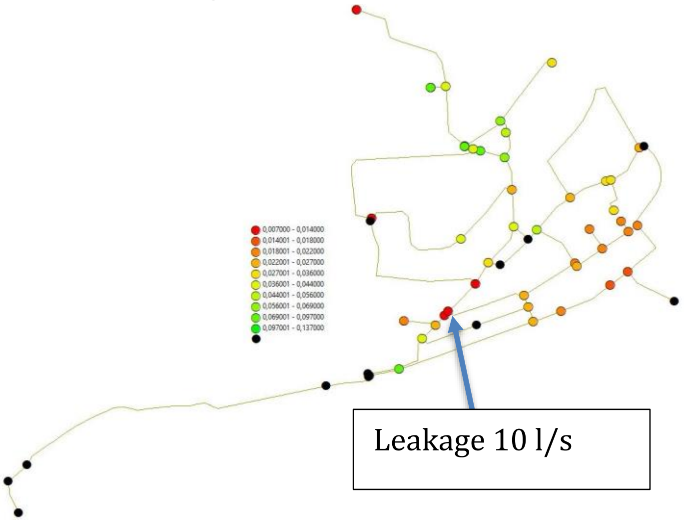


*Figure 21, RMS * STD, first leakage*

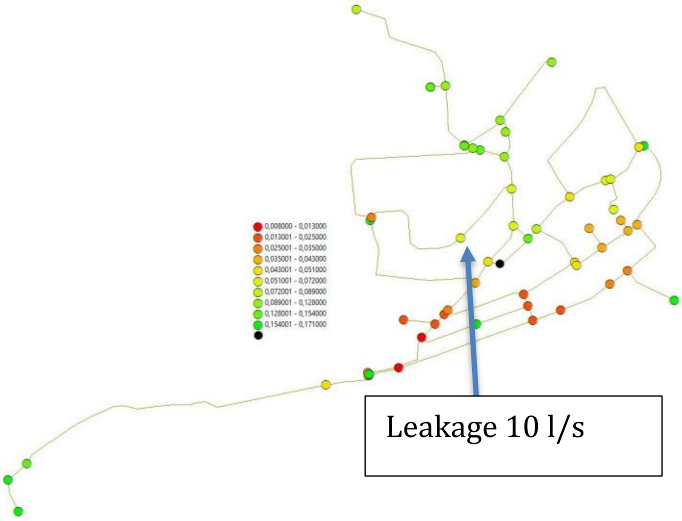


*Figure 22, RMS * STD, second leakage*

The two simulated leakages show similarities in the area chosen for the most probable leakage. Both points are located on larger pipes and only a few points away from each other. The accuracy is not similar as has been described earlier.

4.4 Summation of standardized method

The standardized method described in previous sections consists of three major steps. The main factor to consider in the set-up is the pre-existing conditions. If significant leakage exists in the area, the pinpointing of new leakage could be unfeasible. The area or network should be free of any major leakage before the installation of pressure sensors.

The first step is to physically install pressure sensors in the chosen area. Without any data, the MIKEURBAN model cannot be calibrated, not to mention the impossibility of running the Leak Localization software. The pressure sensors should be located throughout the network to give an accurate overview of the area. The three most important criteria are the size, age and material of the pipes. The grouping of similar pipes is of great benefit to the coming calibration of the MIKEURBAN model. If possible, at least one pressure sensor should be installed in each of these created groupings to facilitate further investigations.

The second step is to determine the existing conditions in the pipes. The best way to do this is to calibrate an MIKEURBAN-model based on the pressure and flow measurements received from the area. With the real-world conditions simulated as accurately as possible, the next steps will be much more accurate.

The third step is either to experiment with the leak localization software to verify validity in the area or to wait until a real-world leak is encountered. Either way, the difference between the real-world measurements after the leak and the MIKEURBAN-model will be compared and inserted in the Leak Localization software alongside the rest of the information regarding the area. The results from the software can then be transferred to ARCMap, or any other GIS-program that may open table data, from comma-separated value files (e.g. .csv files) and display the resulting maps.

With these values, the area in which the leakage is located can be narrowed considerably, making the work of finding and repairing the leakage much easier.

5. Discussion

5.1 Internal and external system

When using the external system of pressure sensors, the positive and negative became abundantly clear. When creating the leakage by extracting 10 l/s, the flow more than doubled but the pressure did not drop as significantly, from around 90 m to around 89 m. There were no problems at all with setting up the pressure sensors, but the data was lacking when comparing to other methods of data gathering such as flow measuring. Only when the flow was increased to 30 l/s during the capacity test did the pressure drop significantly, by almost 6m. Due to physical restrictions in the pipes, the capacity test of 30 l/s could only be performed in one location, thus making it impossible to compare. The maximum leakage that could be compared was 10 l/s. Despite this, the computational power of the Leak Localization software was impressing. Disregarding the usage difficulty of the software and the cumbersome methods of inserting data, the internal system did its job satisfactory with the first leakage. Handling small pressure changes and a rough calibration of the MIKEURBAN model, the results from the first simulated leakage was clearly satisfactory. Given a real-world scenario, the results would be enough to narrow down the search radius significantly based on where the model indicates leakage. The second leakage highlighted the uncertainties in the Leak Localization software. The reason the results from the first leakage is more accurate than the second leakage is yet unknown. The roughness and dimension change could be more accurate to the real-world situation in the larger pipes than the smaller pipes.

Comparing the strengths and weaknesses of this system, it quickly became clear that this method of leakage localization has very high potential. Extracting pressure data in field is currently expensive, but with new technology in the form of pressure sensors that can withstand water hammers, this will change. With that change, I believe that most if not all methods will include pressure measurements to validate the results when available. A combination of factors will be the future of the industry since no single method can precisely locate all leakages in all pipes without labor-intensive and time-consuming procedures.

Another factor that was confusing during this process is the absence of proper MIKEURBAN-calibration methods. The possibility of fully replicating a real-world pipe network, with roughness and diameter change is of paramount importance for the future. During this project several tens of hours was spent by only calibrating the MIKEURBAN model. In a real-world situation, this is completely unacceptable for such a small area. The need for proper, automated calibration software is high and will increase in the future. The hardware to calibrate roughness and dimension change is currently also lacking. It is possible to apply pressure sensors to the areas where the need for calibration is high, but no whole system approach has been explored as explained earlier. Perhaps the emergence of Machine Learning, a method to completely calibrate a drinking water network based on flow measurements and pressure measurements will emerge.

5.2 Comparisson of effectiveness

Comparing the amount of work to initialize different methods of leakage localisation methods, the Leak Localization tool is currently one of the harder methods. The lack of a perfectly mapped and optimized MIKEURBAN model is a severe hindrance. In addition, not many points where data is collected exists in todays water distribution network.

Smartball techniques, radar and probes are all more suitable for todays networks, based on amount of work per litre leakage found. This is however limited to new implementation of techniques. With continous usage and a properly calibrated MIKEURBAN model, the benefits of Leak Localization tool and pressure based leakage localisation become evident. With the emergence of more data from all parts of the system, the model based leakage localisation will be improved and become the most efficient form of localisation.

5.2.1 Positive aspects of Leak Localization

The best and most positive aspect of the Leak Localization software is the ability to passively observe a drinking water network and only operate when changes occur. The possibility of fully taking over large scale monitoring in combination with flow measurements is very promising. The amount of work for the staff responsible for maintenance of the drinking water network will decrease sharply. The focus of the staff will be to use small-scale leakage detection to exactly locate the leak and to repair the pipe. The amount of manpower needed to repair drinking water networks will decline substantially. With a lowering of man-hour, the cost of maintenance will also decrease.

5.2.2 Negative aspects of Leak Localization

The negative sides of Leak Localization is several at the moment. No automated process for the calibration of the MIKEURBAN model is widely used, making the calibration slow and time consuming. The Leak Localization software is not user-friendly and no smooth transition between SCADA systems and the software exist. The values needs to be manually imported, a very time consuming process. The pressure sensors need to be installed in several places, making the process very expensive. In addition, the sensors need constant maintenance and with a large network, there will be hundreds of sensors to maintain.

The results aquired from this investigation reveal a lack of precision. The need for smaller, more precise methods to exactly locate the leakage currently exists to aid the maintenance of the pipes.

5.2.3 Current effectiveness

To fully incorporate this method as the prime leakage localisation method used is impossible. The economic constraints, the lack of proper pressure sensors capable of measuring for years and the unrefined method of usage is a severe hindrance. All methods of leak localization have their downsides and ineffectivenesses. The software Leak Localization have too many downsides compared to the benefits. At the moment, the other methods of leakage localisation, such as smartball techniques, ground radar and hydrophones have all shown their effectiveness in fully locating leakage given the right conditions. Understandably, the Leak Localization software is mothballed until further notice. The effectiveness of the method is simply too low.

5.2.4 Future potential

Despite all the negative aspects and the current unavailability of constant pressure measurements, the potential of the Leak Localization software is very good. All the negative sides are possible to counteract in the future and several of the negative aspects are being improved as we speak. The pressure sensors are evolving at a very high rate, the interest in calibration tools are rising and with more demand, the possibility of evolving the software is considerable. For example, Sustainable Waste and Water, City of Gothenburg is currently searching actively for methods of implementing more pressure sensors in their existing system. An addition of pressure sensors will be extremely beneficial to software such as Leak Localization.

The most promising path to take next is the combination of flow measurements and pressure measurements. Both are measured currently and with an increase in data, several avenues of experimentation exist. For example, if the drinking water network is supplied by two points with a flow measurer installed, it is possible to compare the normal situation to the altered situation caused by a leak. If the flow is usually similar in both points, a higher increase in one flow meter during a leak may reveal additional information regarding the location of the leakage. Combining this information with the data from Leak Localization may yield even more precise results. In addition, both flow measurements and pressure measurements would be passively measuring and only activate when a leak is located. The workload is as previously mentioned much lower when no active surveillance needs to be done.

6. Conclusion and further work

6.1 Conclusions

The outcome of this project resulted in the following conclusions

- The automated process of leakage localization through modelling has a very high potential but is currently untested in large-scale real-world situations
- The software Leak Localization needs further studies to verify accuracy and further work to integrate it into MIKEURBAN, thus making it more user friendly
- With further trials regarding pipe size and roughness, the area of pressure-based leakage location may rise in popularity
- New innovations are necessary to allow more pressure sensors to be placed. The pressure sensors must manage water hammers efficiently.

6.2 Continuation of work

Several avenues of continued investigations arose during the trials. The uncertainties regarding the second simulated leakage are unexplained and requires further work. The pressure changes of the second leakage was smaller than the pressure changes of the first leakage despite being exactly alike. Does this mean the pipe diameter affects the accuracy of the results? Is one of the weaknesses of the Leak Localization software the inability to find leakage in smaller pipes? Some of the data collected indicate this weakness, however it is not certain and further studies needs to be performed.

The second possibility is the calibration of the MIKEURBAN-model was insufficient. As can be seen in chapter 3.7, the subgrouping of pipes may interfere with the actual conditions of the pipes. The assumption that similar age, material and location will lead to similar roughness and diameter change may be incorrect. This could be investigated further, to great benefit of future roughness calibration methods. The more precise the MIKEURBAN-model, the more precise the values from the Leak Localization software.

The most pressing concern is the development and distribution of a roughness/diameter change software. Given pressure data, the information regarding the pipes, the flow measurements and any and all other data available, it should be possible to extrapolate a calibrated MIKEURBAN-model that may serve as a basis for leak localization and pipe renewal in the years to come. The ability to make leakage localization an automated process is very important to keep costs down in order to manage the difficulties in the future.

7. References

DHI, *MIKE URBAN-Integrated Urban water modelling*, 2019. Available at https://www.mikepoweredbydhi.com/products/mike-urban/

European Environment Agency, *Use of freshwater resources in Europe*, 2019. Available at https://www.eea.europa.eu/data-and-maps/indicators/use-of-freshwater-resources-3/assessment-4

Sustainable Waste and Water, City of Gothenburg, *Pipe Material, Annual report* 2019. Responsible author: Jacob Ljungqvist, 031-368 71 96

UNESCO report *Wastewater, the Untapped Resource*, 2017. Available at: https://unesdoc.unesco.org/ark:/48223/pf0000247553

Water Intelligence, *Water Facts*, 2019. Available at: http://www.waterintelligence.co.uk/water-facts/

Atef, A., Zayed, T., Hawari, A., Khader, M. and Moselhi, O. (2016) *Multi-tier method using infrared photography and GPR to detect and locate water leaks*. Automation in Construction.

Grafarend, E.W., (2006) *Linear and Nonlinear Models: Fixed Effects, Random Effects, and Mixed Models.*

Ingeduld, P., (2016) *Technical note, Leak Localization Tool.* Available at DHI.

Kaur, K., Annus, I., Vassiljev, A. and Kändler, N. (2018). *Determination of Pressure Drop and Flow Velocity in Old Rough Pipes*.

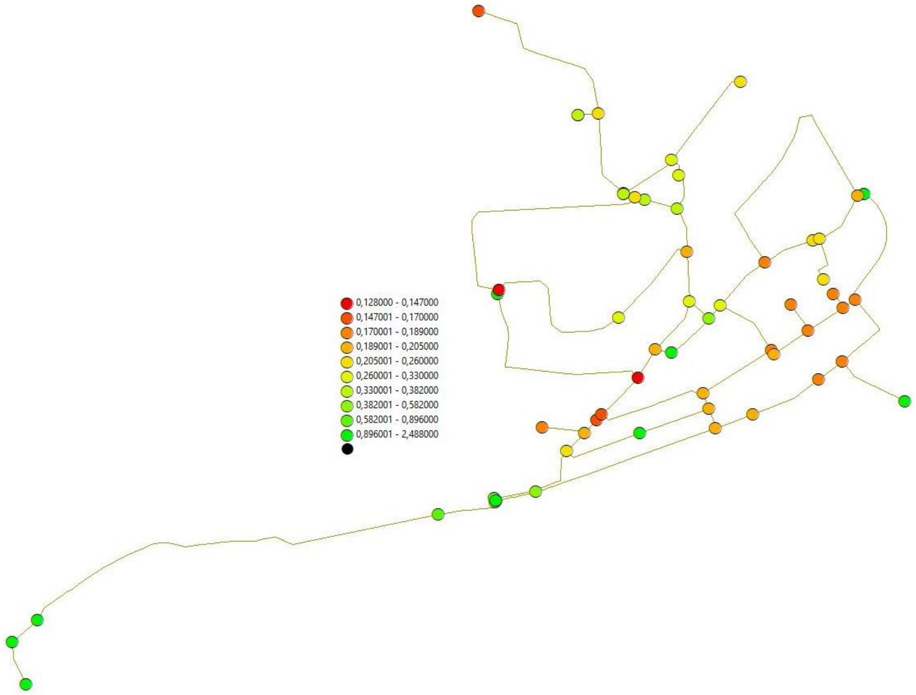
Lah A. A. A., Dziyauddin, R. A. and Yusoff, N, M. (2018). *Localization Techniques For Water Pipeline Leakages: A Review*.

Mergelas, B. and Henrich, G., (2005). *Leak locating method for precommissioned transmission pipelines: North American case studies. Leakage 2005*.

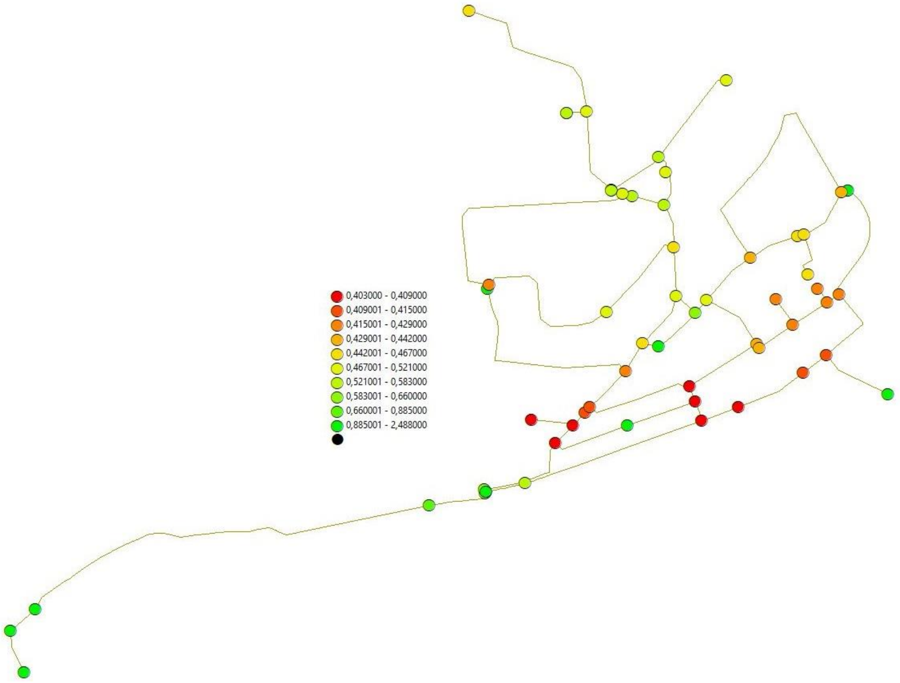
Perelman, L. S., Abbas, W., Koutsoukos, X. and Amin, S. (2016). *Sensor placement for fault location identification is water networks: A minimum test cover approach.*

Appendix 1, Complete results

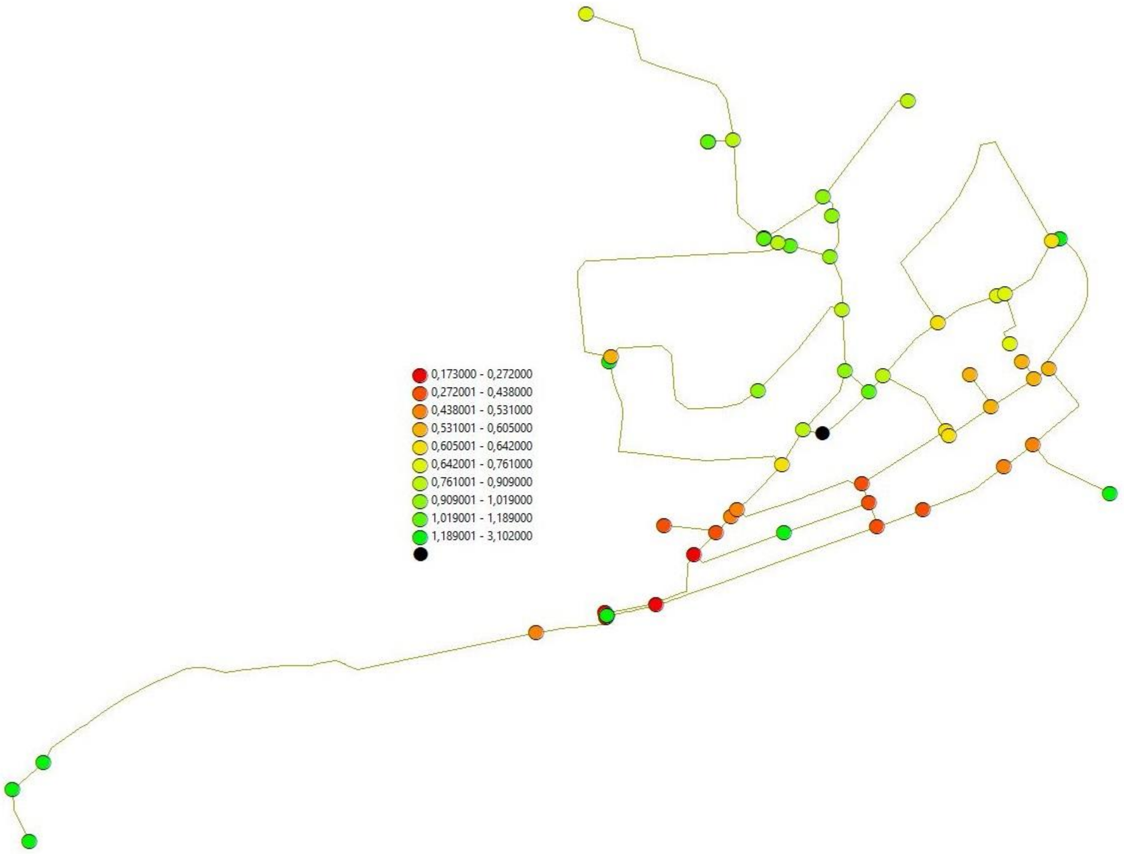
Simulated Leakage 1:



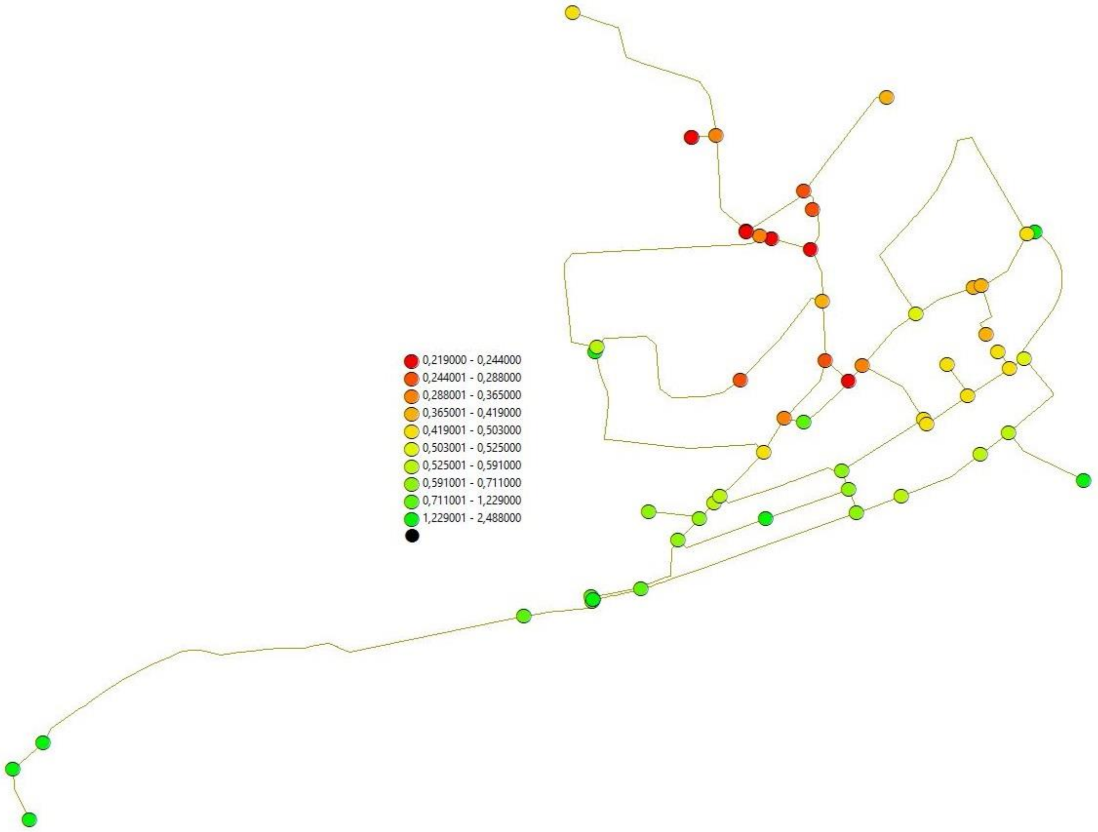
RMS Actual, first simulated leakage



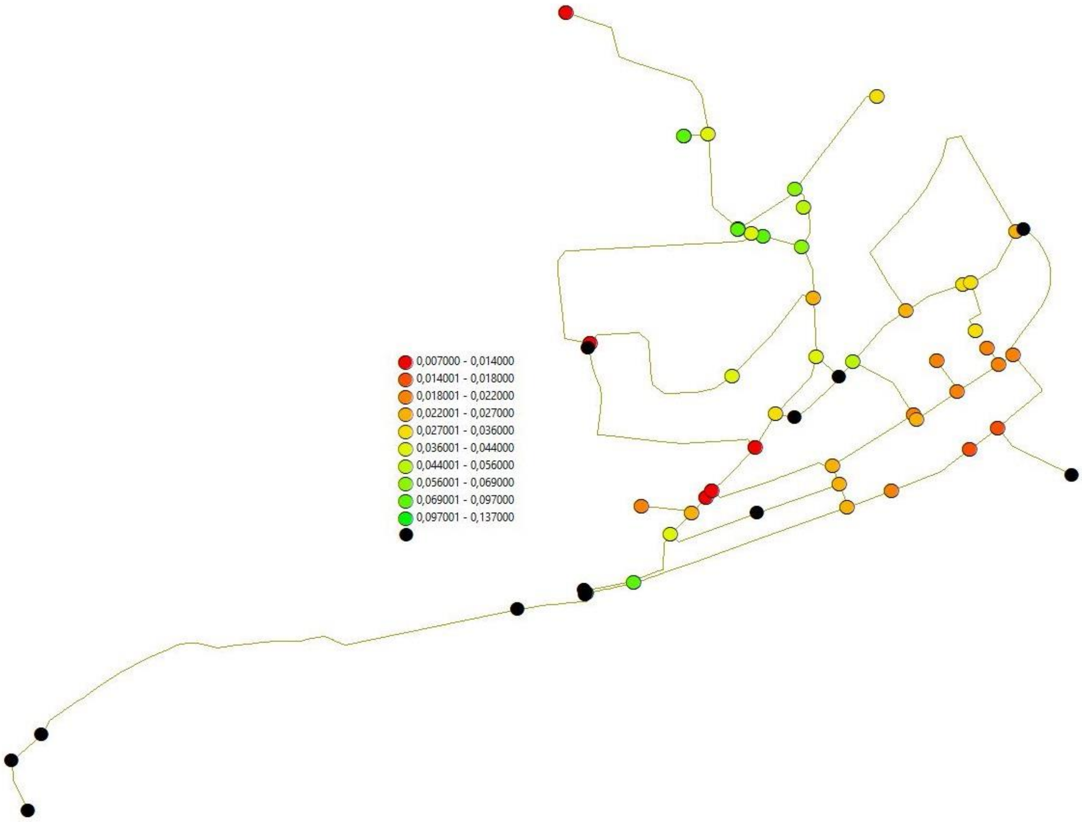
RMS Average, first simulated leakage



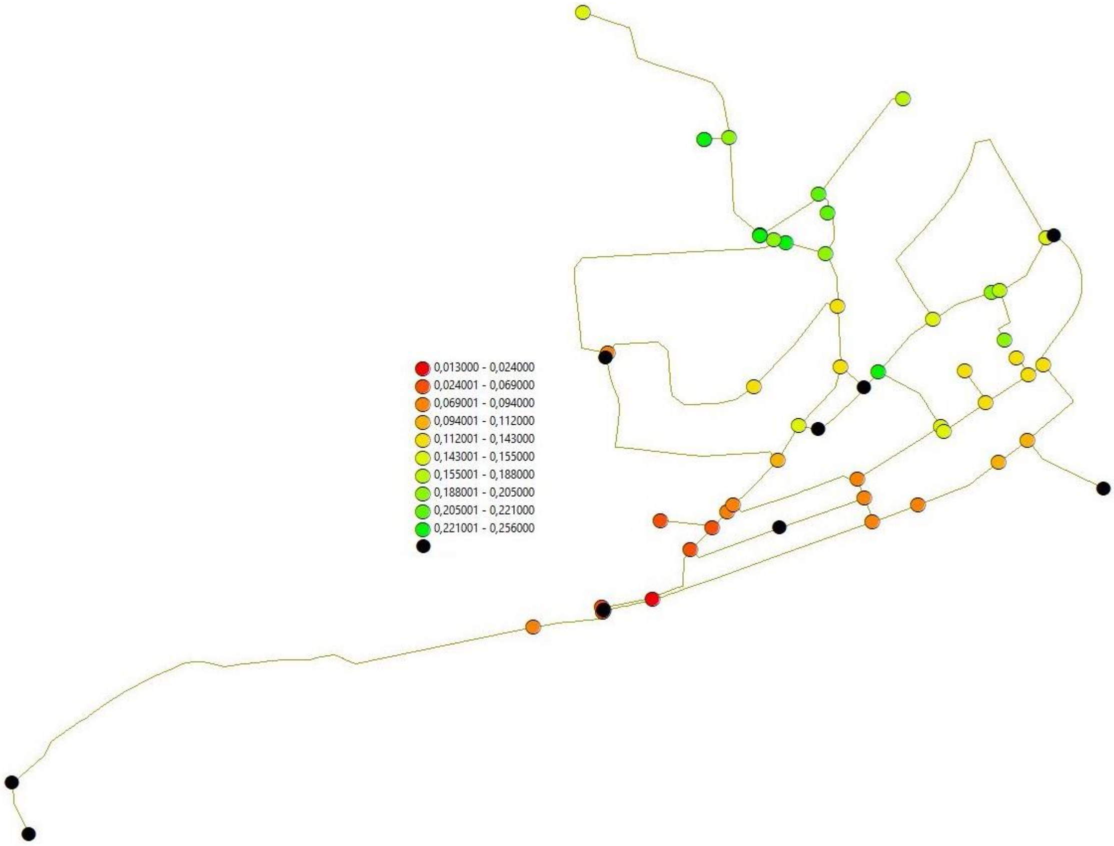
RMS Max, first simulated leakage



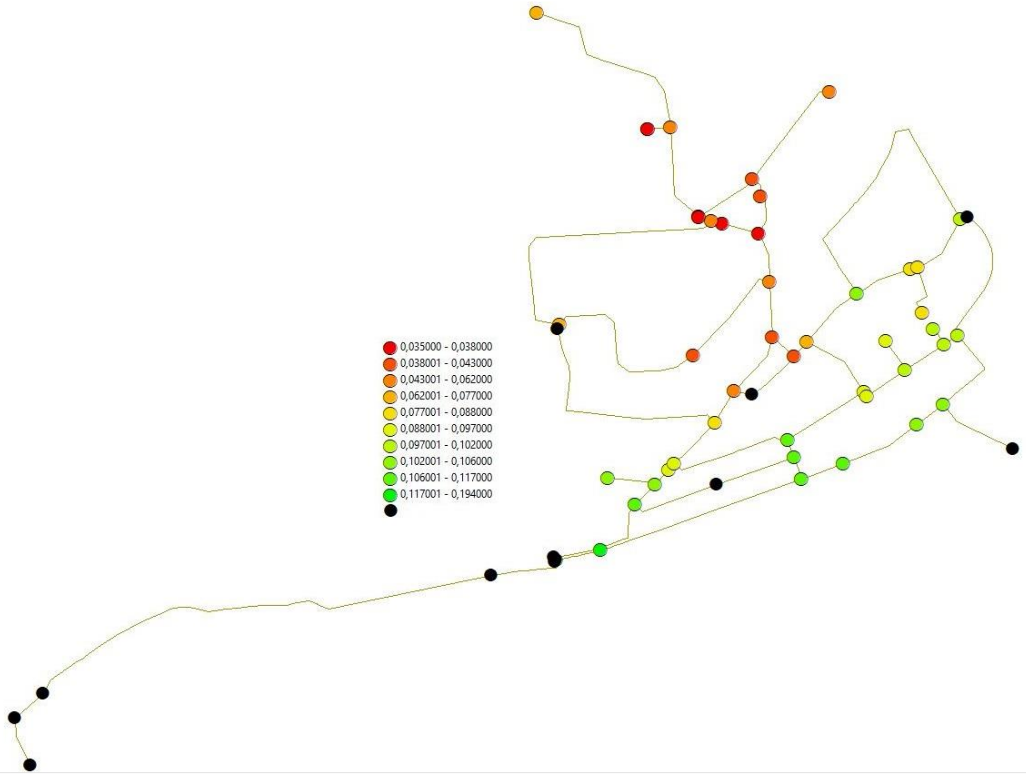
RMS Min, first simulated leakage



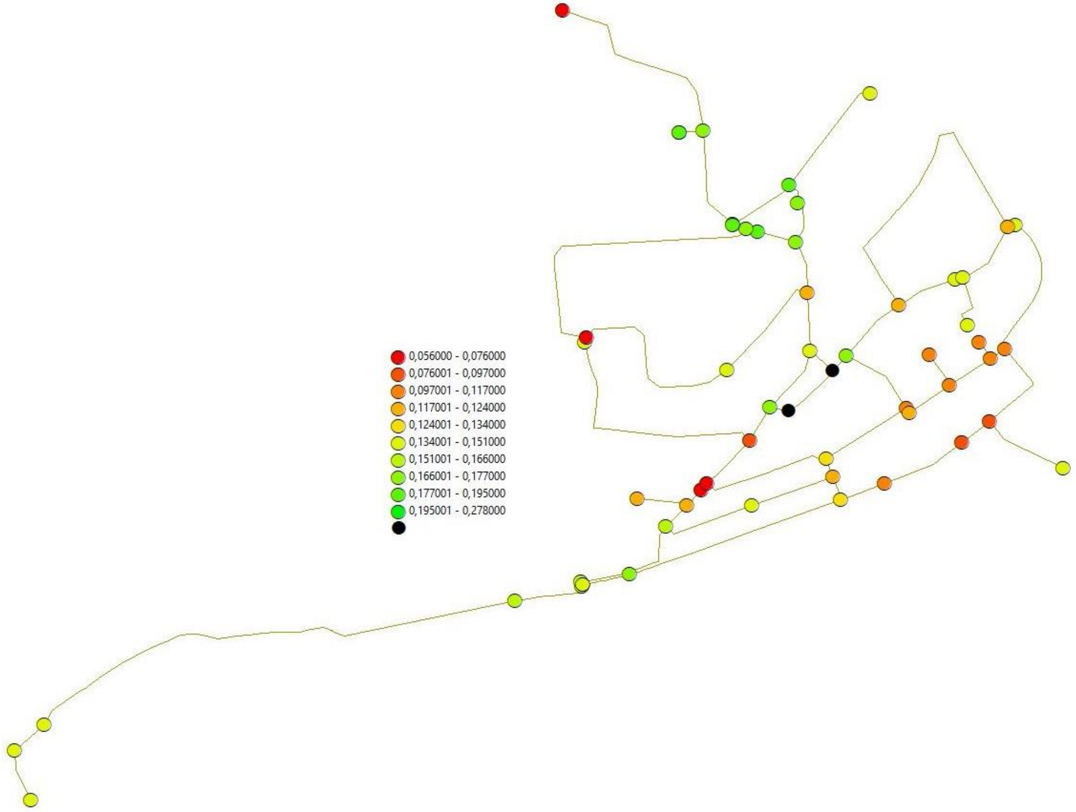
RMSxSTD Actual, first simulated leakage



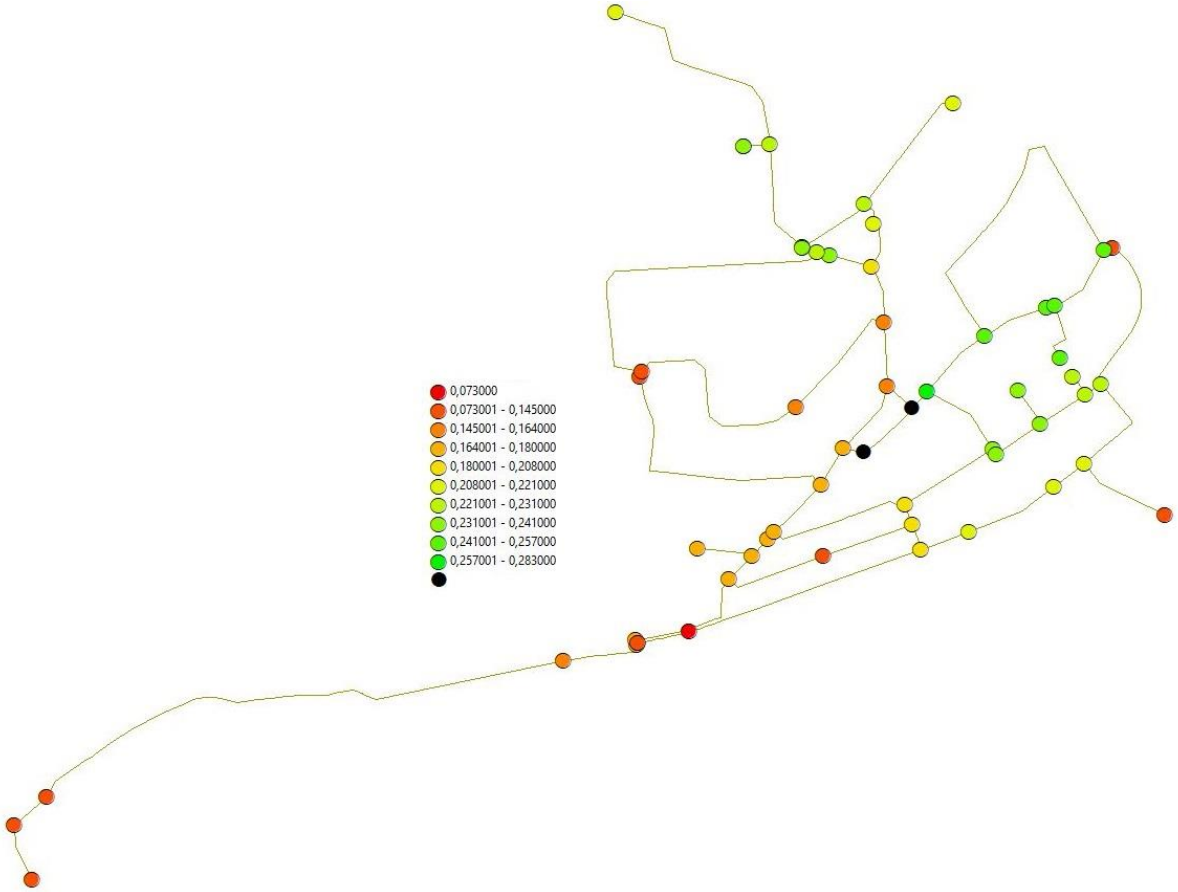
RMSxSTD Max, first simulated leakage



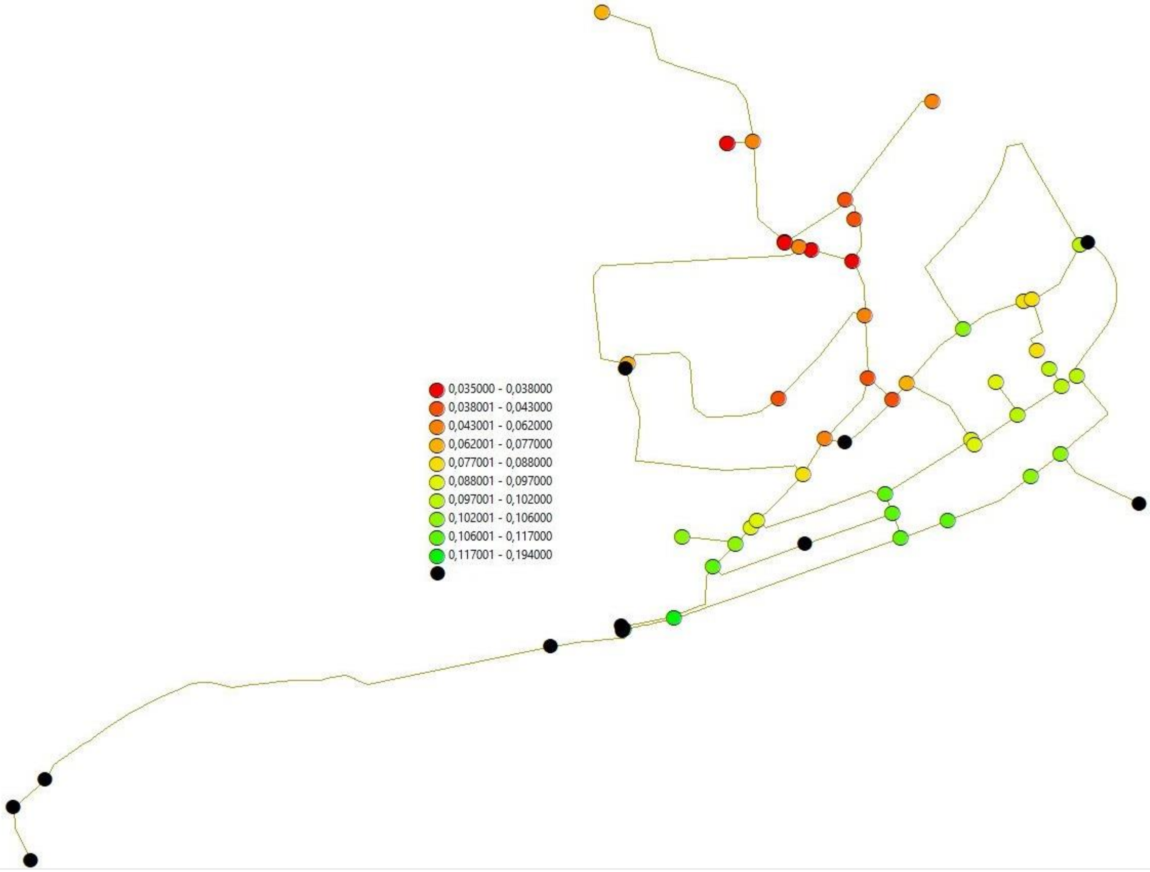
RMSxSTD Min, first simulated leakage



STD Actual, first simulated leakage

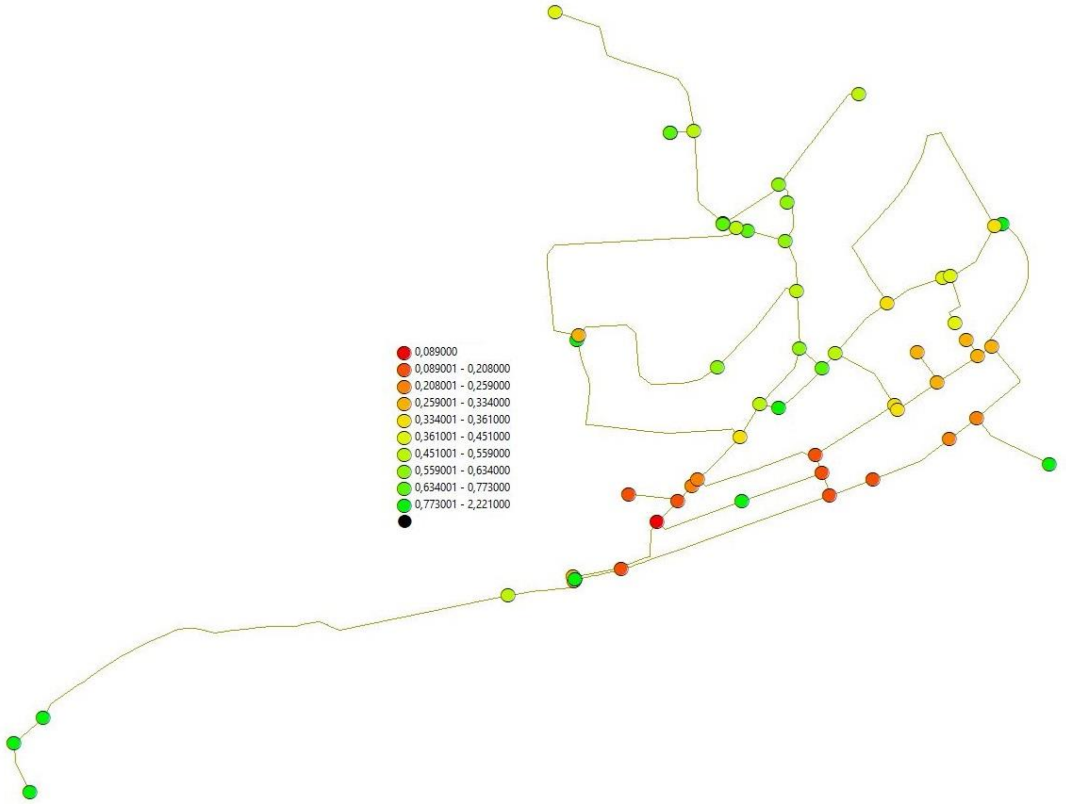


STD Max, first simulated leakage

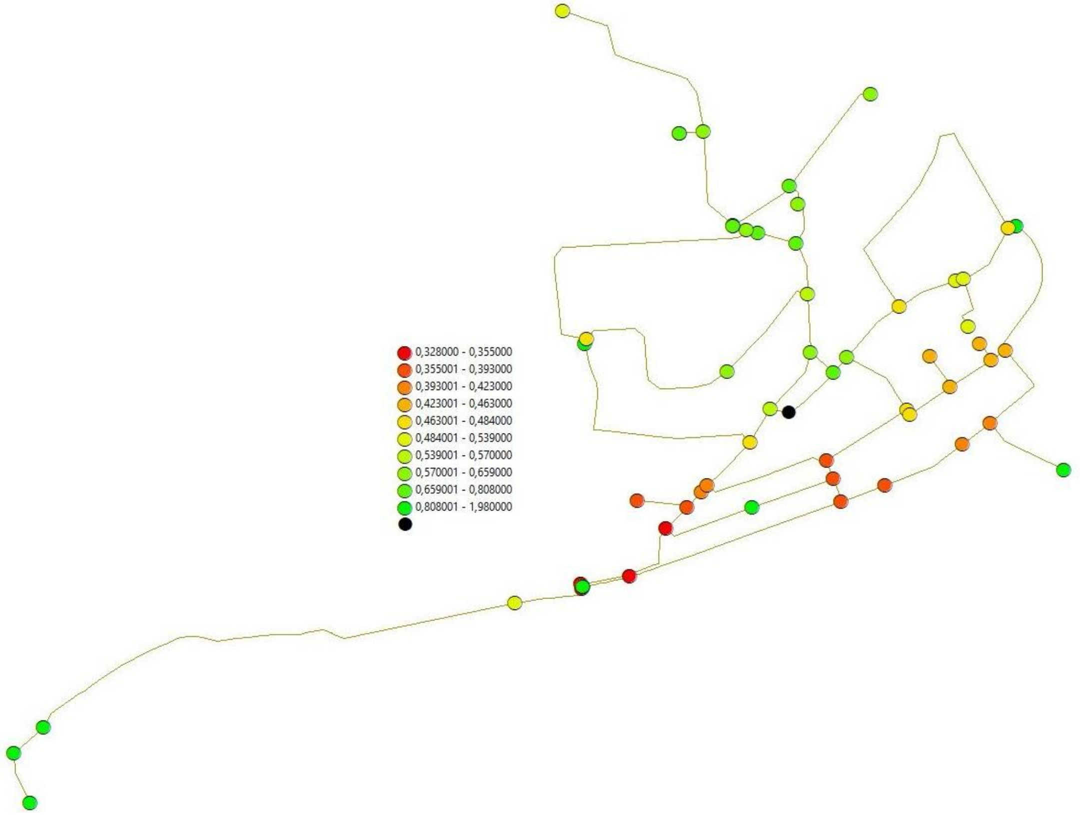


STD Min, first simulated leakage

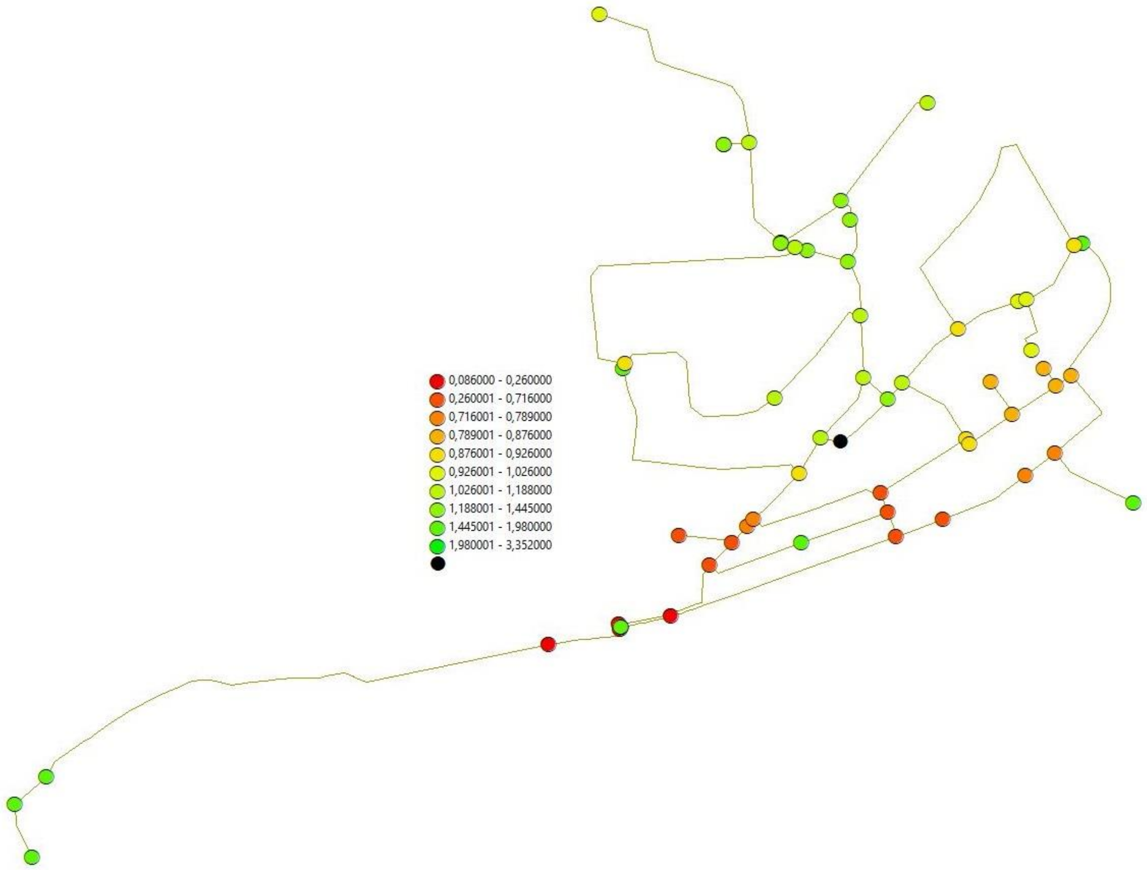
Simulated Leakage 2:



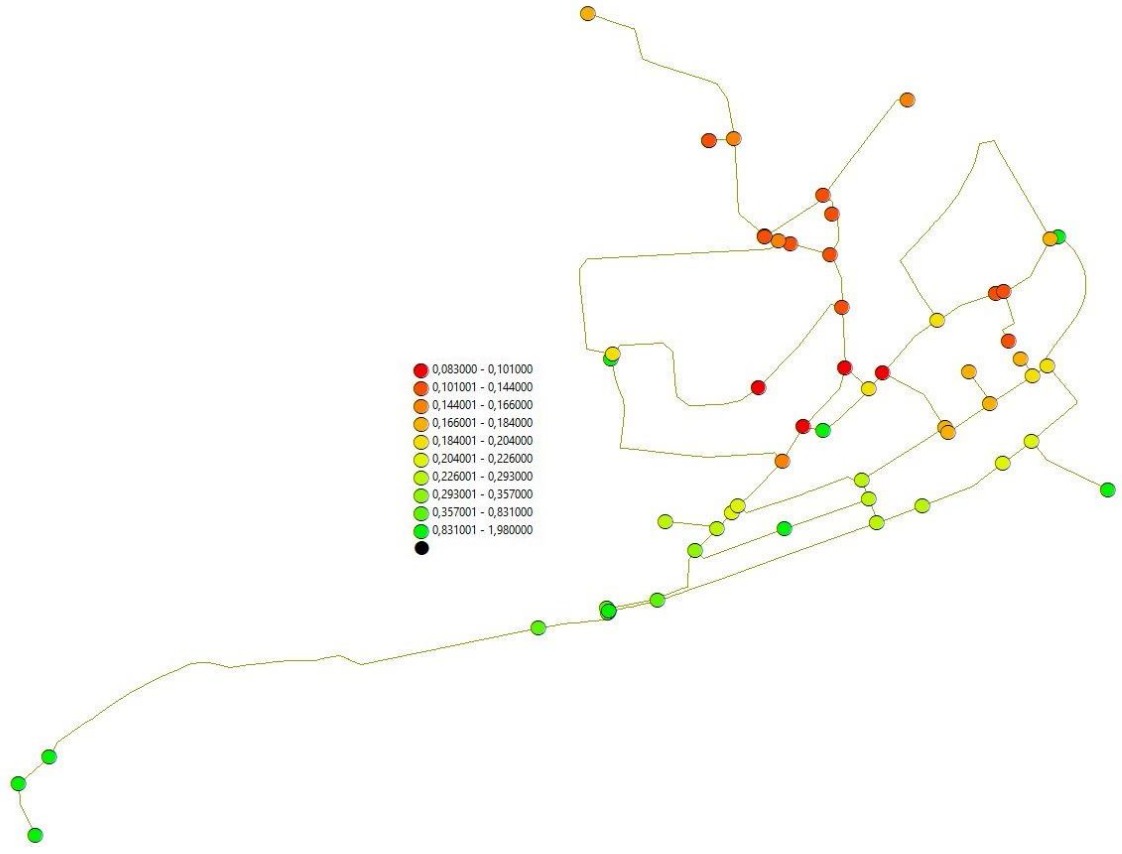
RMS Actual, second simulated leakage



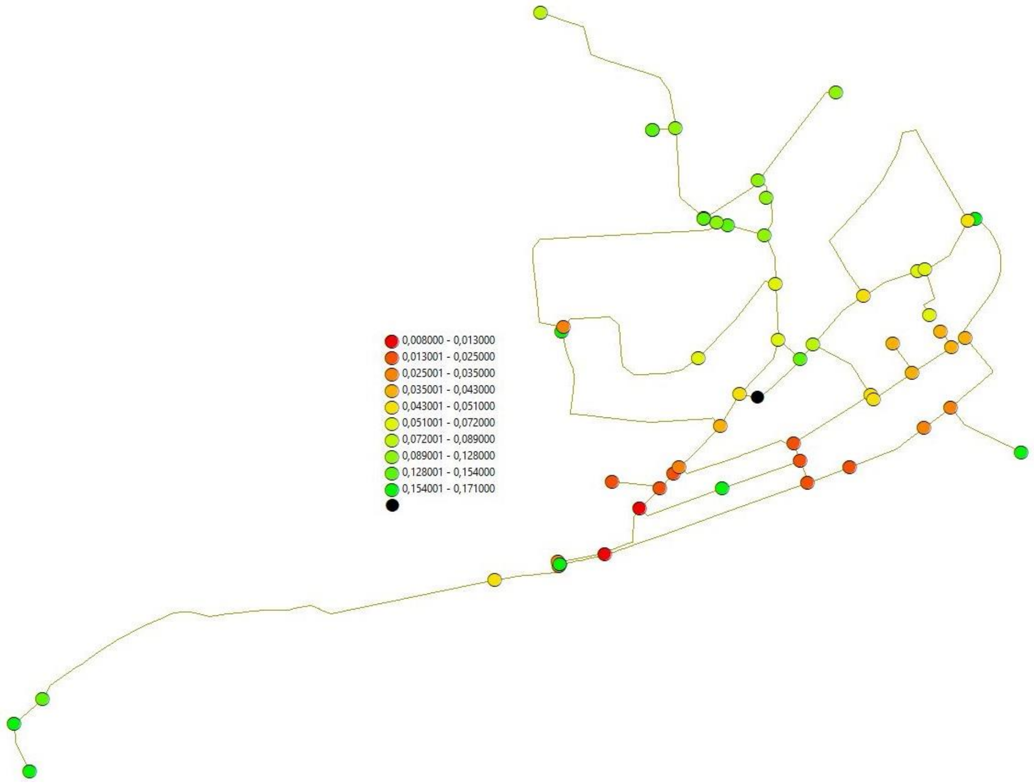
RMS Average, second simulated leakage



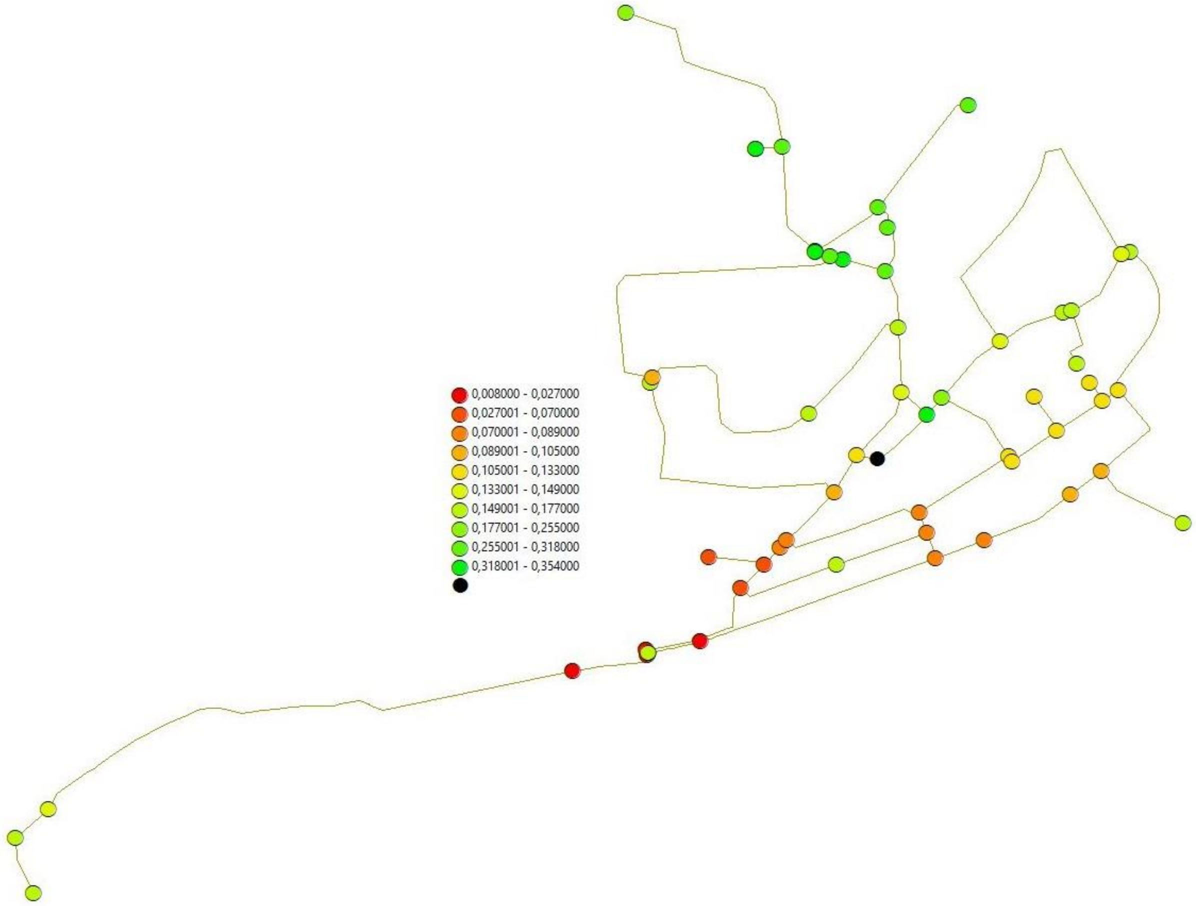
RMS Max, second simulated leakage



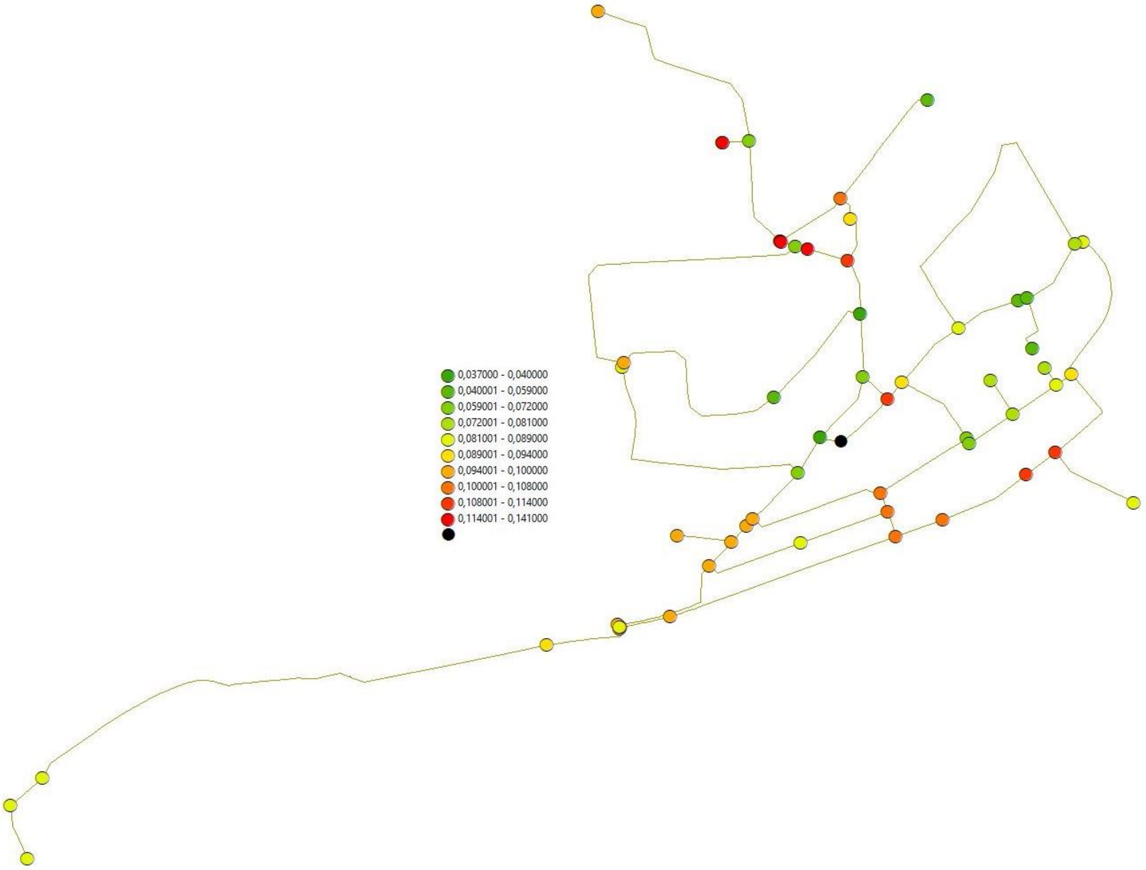
RMS Min, second simulated leakage



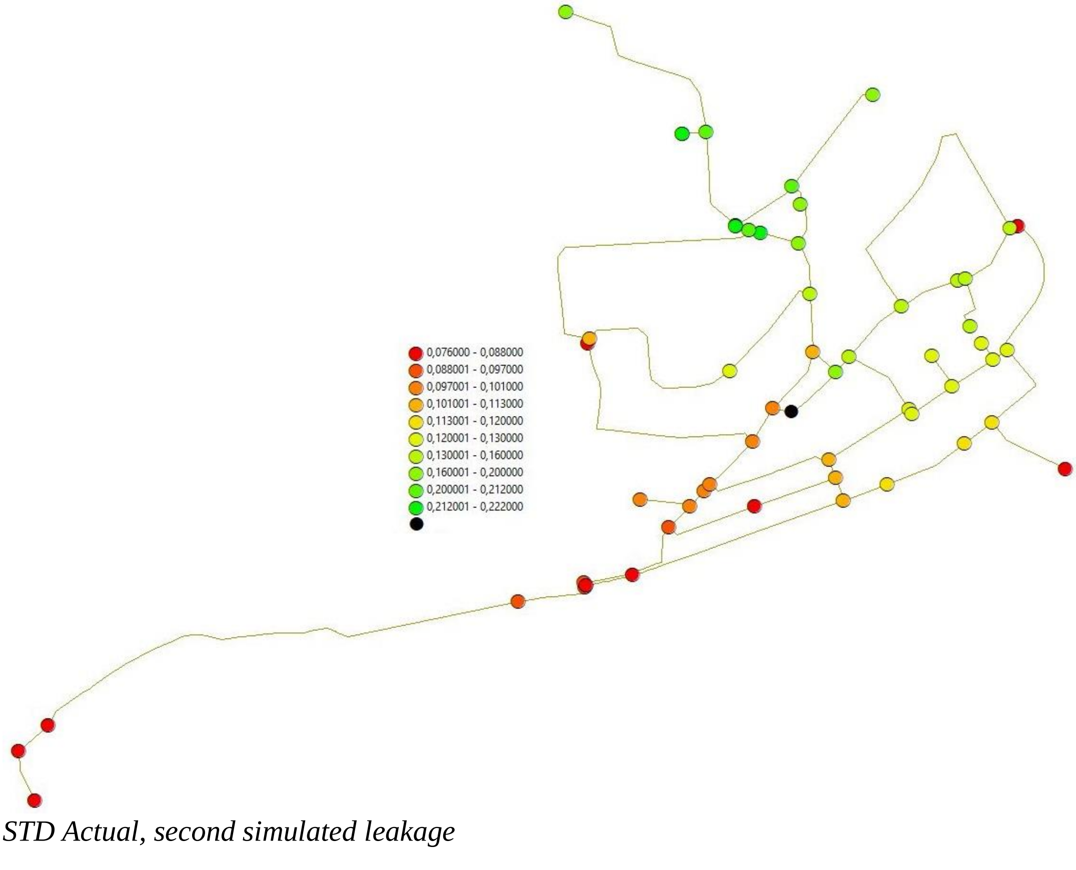
RMSxSTD Actual, second simulated leakage



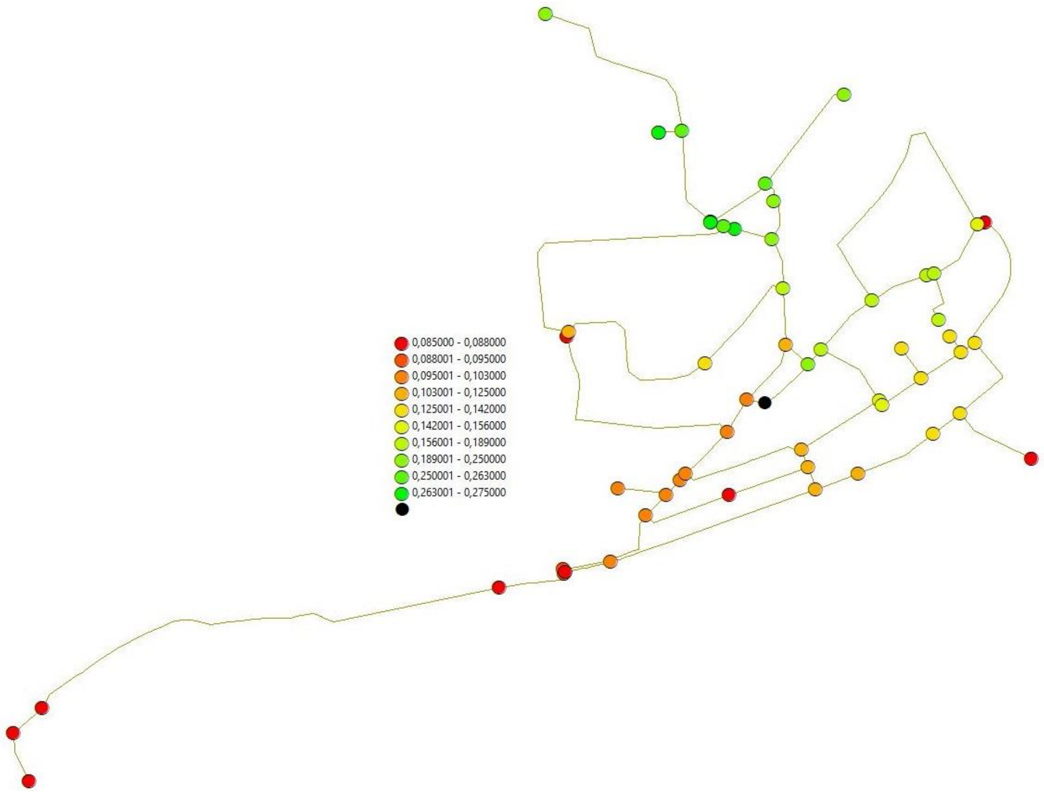
RMSxSTD Max, second simualted leakage



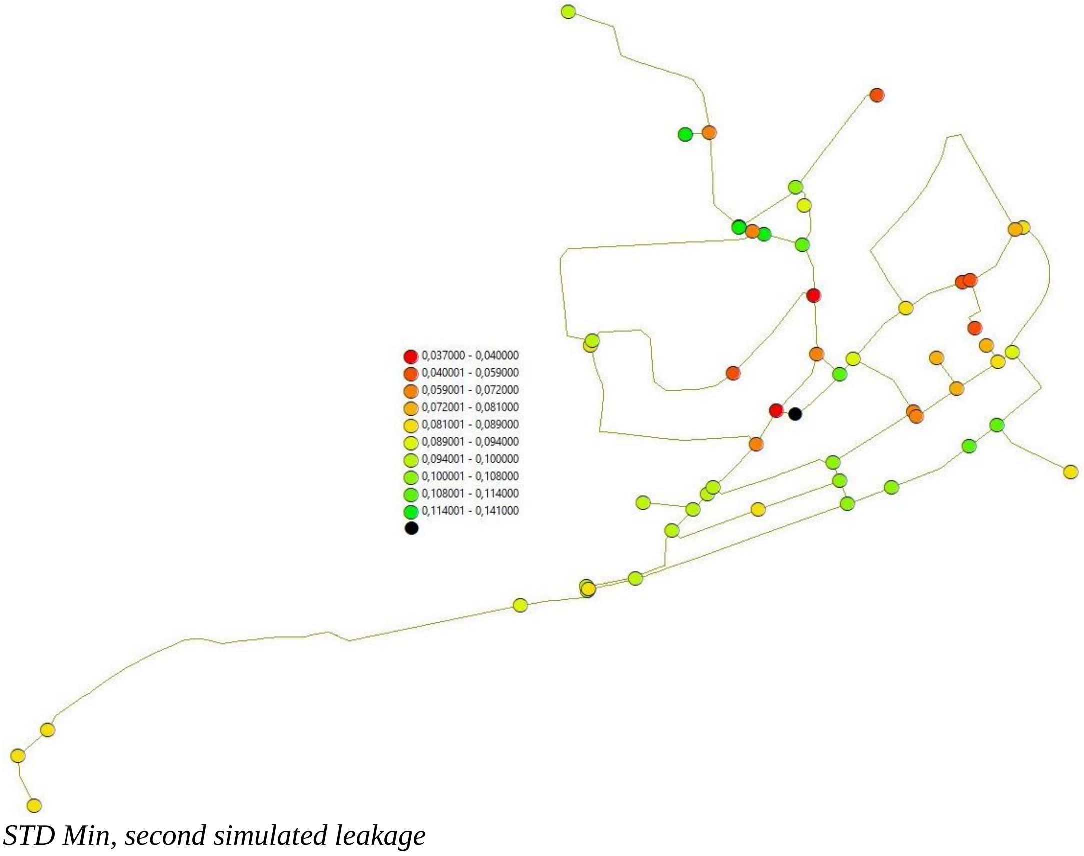
RMSxSTD Min, second simulated leakage



STD Actual, second simulated leakage



STD Max, second simulated leakage



STD Min, second simulated leakage