SAVONIA

OPINNÄYTETYÖ - **AMMATTIKORKEAKOULUTUTKINTO**
TEKNIIKAN JA LIIKENTEEN ALA

DYNAMIC HYDRAULIC MONITORING IN DISTRICT METERING AREAS

AUTHOR: Jarno Mäkelä

SAVONIA-AMMATTIKORKEAKOULU

OPINNÄYTETYÖ
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Tiivistelmä

Tarpeet aluemittausjärjestelmille talousvesien vesijohtoverkostoissa kasvavat jatkuvasti infrastruktuurin vanhetessa ja verkostojen laajentuessa. Vaikka hydraulisesti suljetuilla aluemittausjärjestelmillä on päästy hyviin tuloksiin hukkavesien määrityksessä, voidaan järjestelmiä silti kehittää yhä kattavemmiksi, tarkemmiksi ja tehokkaammiksi.

Tämän opinnäytetyön tarkoituksena oli suunnitella ja kehittää uudenlainen automaattiseen monitorointiin perustuva dynaaminen seurantamenetelmä aluemittausjärjestelmiin ja testata sen toimivuutta käytännössä. Aluksi kehityssuuntaa kartoitettiin vesilaitoskyselyllä, jonka tulosten perusteella halutun järjestelmän ominaisuudet määritettiin. Opinnäytetyössä kehitettiin tietokoneohjelma, jonka avulla voidaan seurata mittauspisteissä tapahtuvia reaaliaikaisia muutoksia dynaamisesti käyttöön perustuvan normaalitilan perusteella ja automatisoida hälytykset verkoston häiriötilan ilmetessä.

Opinnäytetyö liittyy monikansalliseen Water-M -projektiin, jonka Suomen osuuden on rahoittanut Tekes. Opinnäytetyössä kehitettyä ohjelmaa tai sen toimintaperiaatetta voidaan hyödyntää aluemittausjärjestelmissä, tai muissa vastaavissa systeemeissä joissa jatkuvatoiminen mittaus on tärkeä osa toimintaa.

Avainsanat
Aluemittausjärjestelmä, data-analyysi, dynaamiset raja-arvot, jatkuvatoiminen mittaus, MATLAB

SAVONIA UNIVERSITY OF APPLIED SCIENCES — THESIS
Abstract

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Abstract

The desire for district metering areas in water supply networks is increasing continuously. Aging of the infrastructure increases occurrences of leaks in the network and expansion poses problems in efficient management of the system. While district metering areas have shown good results in the reduction of non-revenue water, the systems can further be improved to be more comprehensive, precise and efficient.

The goal of this thesis was to design and develop a new dynamic monitoring method based on automatic measurements and to test its usage in practice. At first the development direction was outlined by creating a user survey of needs in water supply networks directed at technical personnel operating and monitoring these systems. According to these results, monitoring software was designed and programmed. With this software, real-time changes in the measurement points can be monitored dynamically based on the normal state usage profile created from usage data and automate alarms when anomalies are detected.

This thesis is related to the transnational Water-M project, of which the Finnish portion is funded by Tekes. The developed program or its operating principle can be implemented in district metering areas, or other similar systems where continuous measurement is an important part of the operations.

Keywords
Continuous measurement, data-analysis, district metering area, DMA, dynamic limit values, MATLAB

FOREWORD

This thesis proved to be a challenging, inspiring, rewarding and educational task. I am grateful to every person who made this possible and supported me during this project. Also I would like to thank the Water-M project, which goal is to create a unified water business model, for this opportunity and the funding of this work.

Kuopio 25 August 2016
Jarno Mäkelä

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1 INTRODUCTION

Present day problems in water supply networks come from aging and increase in failures in the water supply network infrastructure, which in turn can result in the increase in water losses and quality issues in the supplied water. Currently these issues are countered by implementing District Metering Areas (DMAs) that are used in water supply networks to bring a more efficient method of determining anomalies in the systems. While the use of DMAs is becoming more common, the methods of finding anomalies are always in the need of improvement. (Allen, M et al. 2011)

The aim of this thesis is to demonstrate how a dynamic hydraulic monitoring and data analyzation system in water supply network district metering areas can be developed, tested and put into practice. Utilizing a dynamic monitoring system and its interfaces in a DMA has advantages in supporting automation, quicker detection of anomalies and reduction of Non-Revenue Water (NRW). The program is written as a part of a development process related to a transnational Water-M project, whose goal is to establish a unified water business model. The Finnish share of the project is funded by Tekes.

This thesis also demonstrates how a survey of water utilities technical personnel is first implemented to map the needs for automated monitoring and control systems in water supply networks to map the development goals. Its results indicate that hydraulic characteristics of the water supply networks are the most important characteristics to measure continuously. Quality measurements are still considered best to be done inside water supply stations before pumped inside the network, by manual sampling for laboratory analysis and by reactive methods which include reporting of quality changes from consumers. Based on these results, advanced monitoring software is programmed in MATLAB to demonstrate visually how a usage profile is formed based on the long-term data for a measurement point in a DMA and the definition of dynamic limit values in which the real time-measurements are compared to.

Using this software, the user can:

- Import and parse the data in JSON format from the database
- Visually and computationally analyze the validity of the data
- Form usage profiles for measurement points in the network from long-term data
- Define dynamic limit values for the usage profiles
- Compare real-time data to both the profiles and dynamic limit values
- Assign the program to alert the user if the limits are exceeded.

The software is programmed to present profiles, limit values and comparison visually for easier grasp of its logic. In automated mass usage cases, when the DMA grid has from tens to hundreds of measurement points, no such visualization is necessary until the detected abnormal situation needs human interaction.

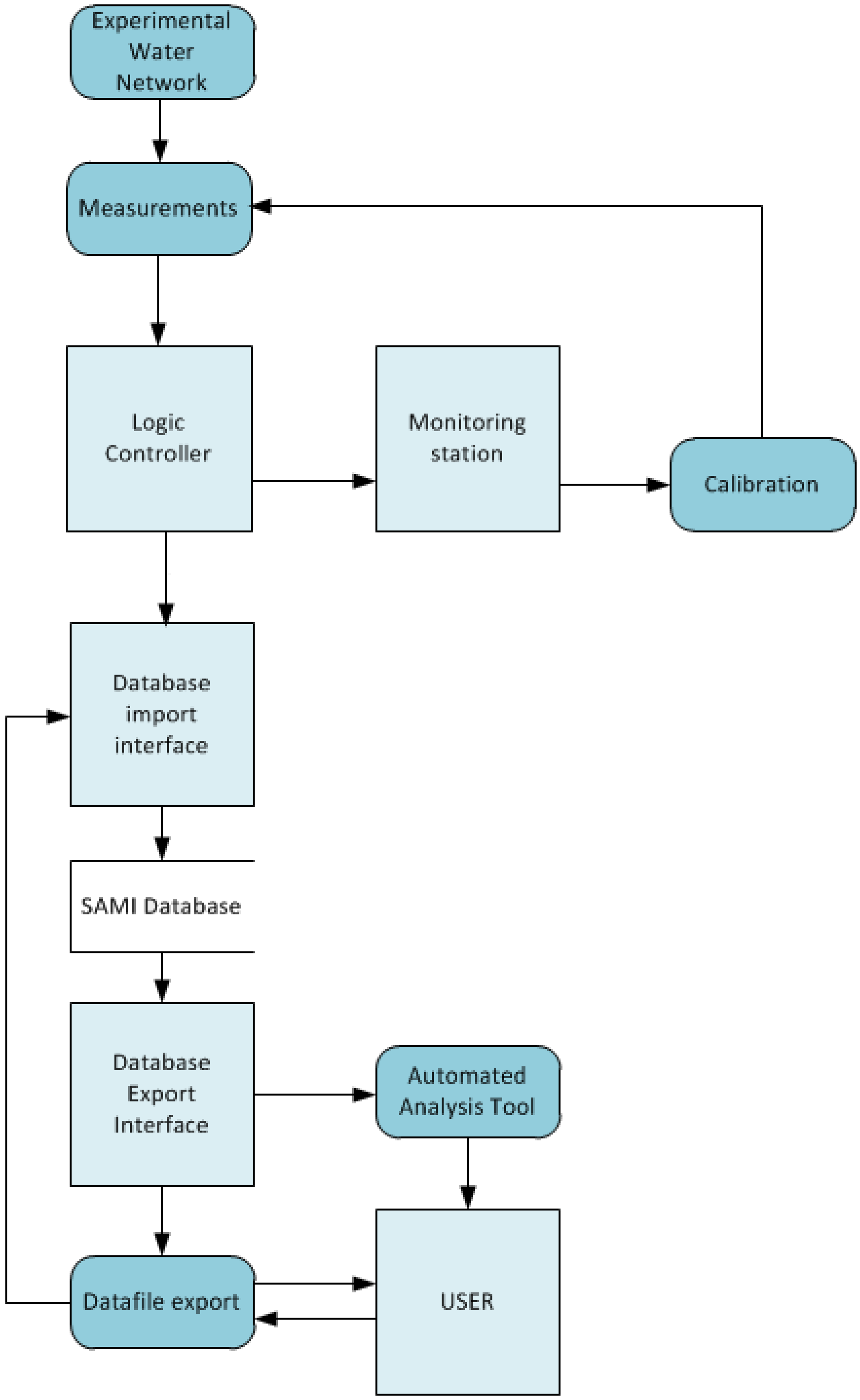


FIGURE 1 Flow chart demonstrating how a monitoring and analysis system functions in the Savonia Pilot scale water supply test network

The district measurement areas used for practical research in this thesis consist of a pilot-scale water supply network test system owned by Savonia University of Applied Sciences and Vehmersalmi district measurement area owned by Kuopion vesi waterworks. The monitoring and analysis is carried out as seen in Figure 1.

2 CONTINUOUS MEASUREMENT, DATA-ANALYSIS AND AUTOMATION

2.1 Continuous measurements and measurement uncertainty

Measurement is a method of obtaining a descriptive numeric value of a measurable physical property of any system that is measurable. It is used in virtually everything where a value is needed to define an attribute for any reason. Measurements can be implemented as one time observations (sampling), or continuous.

Continuous measuring is regarded as an important method of obtaining up-to-date and more comprehensive information from the environment. Contrary to one-time sampling and analysis like in laboratory environments, continuous measuring is typically made by reading sensor data automatically and reacting accordingly or storing it into database for further analysis. It is used on all automated systems, which need continuous observations to perform comparison to the settings and resultant operations.

A problematic issue with one-time, occasional or low measurement frequency measurements is the measurement uncertainty. Measurement uncertainties come from various sources, like accuracy of instruments, natural variation of environmental variables or the measurers themselves. Since the effect of unknown or random variables to the measurement can be reduced by increasing the amount of measures, continuous measurement methods provide consistency and confidence in measurements. For example, an error of unusually large amount of measurable quantity is recorded and possibly taken as granted if the sample is taken once. In this case that could lead to harmful consequences, when measurement-based control is adjusted after the measurement that incorrectly represents the state of the subject, whereas the peak could be exposed by collecting continuous data and analyzing it. This is also how malfunctions and anomalies in the system are often discovered, while one-time sample would not reveal anything about the incidence of the situation, patterns and timings can be extracted from the continuous data records. (Bell, 2001)

2.2 General definition of automation

The International Society of Automation (ISA, isa.org 2016) defines automation as *"The creation and application of technology to monitor and control the production and delivery of products and services."* Automation can be considered as the next step from mechanization, which replaced the need of physical labor in systems. It is usually implemented as a technique to operate processes without direct human control in every step inside the process and also as a linking element with various technologies. Automation is used everywhere in the industry and holds a diverse range of applications from simple monotonous controlling tasks to complex industry production processes. (isa.org, 2016; Kippo & Tikka, 2008.)

Continuous metering and measurements can be held as a basis for automation as all automated processes operate on the measured values. These measurements are continuous and are used to determine the state of the system or the part of it that the automation is designed to make adjustments. Also for a system to be considered automated, it must perform actions or control according to the measurements. If the system only monitors the process and does not make any adjustments, it is considered mainly as an automated data logging station, like in the case of weather stations. The third essential part of an automated system is the control setting that is usually set by operators of the systems. In more advanced settings the control setting may be determined by other automated programs or they can be even determined dynamically based on the analysis of the data. The comparison of measured data is made to the set target value and is required to get the desired results, this is how all automated systems operate. (isa.org, 2016; Kippo & Tikka, 2008.)

At its simplest form, an automated system can be the automatically opening doors with motion sensors at a mall entrance, a more complicated example can be the automated landing process of a space probe. In the case of water distributing systems, automated systems are, for example, used in pump frequency control to maintain stable pressure levels in the network. (isa.org, 2016; Kippo & Tikka, 2008.)

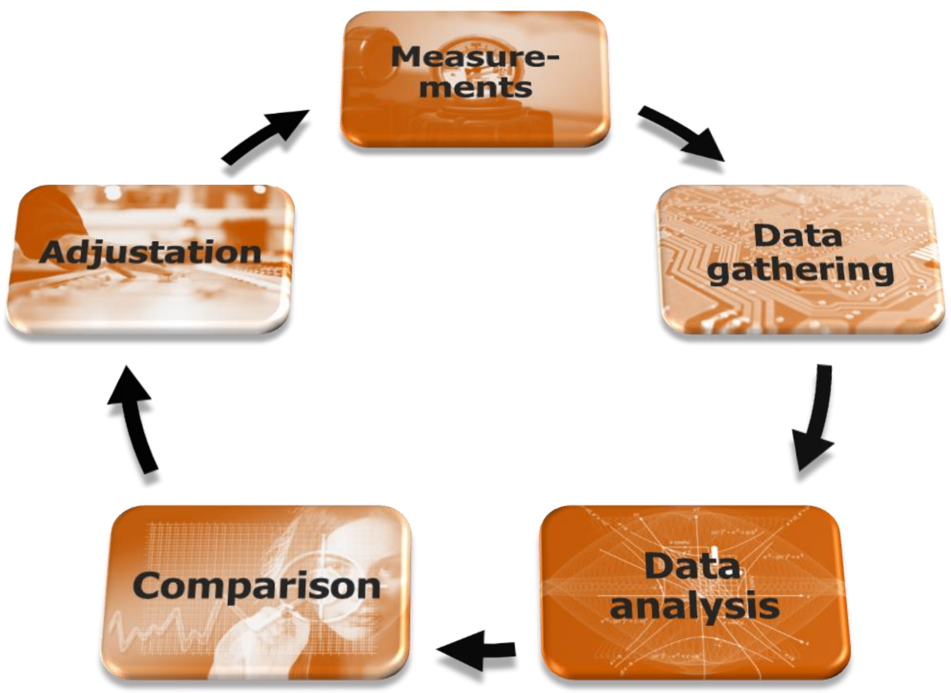


FIGURE 2 How automation works (based on VARMAH, K, 2010)

The flow of automation is represented in Figure 2 and explained here:

- First, the characteristics of the system are measured using various measuring equipment that include sensors, transmitters, logical components, analog signal processing and configuration.
- The data is then gathered and stored into the database in which it can be sorted, filtered and pretreated if needed.
- The data from the database is then imported into analysis that can be an automatic script that checks whether the data is valid, faulty or nonexistent. The data may further be compressed and processed via adjusted methods, or simply a running graph of the data may be formed.
- When the data is processed, a comparison is made with the desired values and the differences are measured and analyzed.
- If the analysis of the measured values reveals its deviation is above certain desired limits, an adjustment of the measured system is carried out by calling a another program that executes the adjustments. If the values are within the limits, the system is functioning correctly.
- After the adjustments, the measurements continue observing the system.

2.3 Uses for data analysis

The modern day computers have significantly more processing power than even ten years ago. Also the amount of collected data has grown dramatically at the same time. This opens new possibilities in data handling, processing and analyzation, all essential in modern day research. Some fields have even become so complex and data-related that handling the data models and processing can be impossible without powerful algorithms and computers. (Turunen, 2012)

The process of data analysis begins with data collecting, and the data is most likely stored in a database in large quantities. Next step is the pretreatment, what includes the removal of measuring errors and deciding over imputation of missing observations. If measurements are being compared, scaling or filtering the data may be necessary. The analysis itself may include, among other things, visualization, regression or categorization of the data. With the analysis, descriptive or predictive models can be created. Descriptive model represents overview of the system where different unfolding events and their effects can be observed, while predictive analysis may be used to make forecasts to calculate future states of the monitored system. (Räsänen, 2011)

Data analysis is used in automation for more specific control and optimization of processes. Models can be created to predict future states of the systems, and based on the data models, dynamic alert states can be defined. Like in this thesis, the built program calculates limit values dynamically based on the profile formed of a long scale of measured and treated data. (Räsänen, 2011)

FIGURE 3 How an extensive overall picture is generated

As seen in Figure 3, an overall picture of the system or a process is generated based on the measured data and is explained here:

- Like in any monitoring system, the monitoring process begins by sensors measuring the desired characteristics of the system. When an overall picture is generated, the measurements must come from multiple locations so that the whole system or process is being monitored simultaneously.
- The sensors transmit the value via a calibrated analog signal that is read by the equipment logic, which in turn returns the represented real value and transmits it to be stored into the database.
- The data is gathered into the database, and especially in the case of an extensive overall status generation, it is stored in large amounts (for example all the data for a day, month, year, etc.)
- The data is imported from the database and analyzed via tools that process the data by filtering faulty data from the data pool, and possibly further process it via various desired methods, that may include averaging, collection spot-specific operations, calculations for the data etc.
- Based on the analyzed data from all points of the monitored system or process, a visualization is generated.

Overall picture of a system or a process can be a hydraulic model of a water supply network based on the features of equipment, or it can be a more recent state of the networks pressure and/or flow in the whole network (i.e. flow rates at every node in the network at specific day to monitor if there are leaks in the system that raise the flow rates).

3 DISTRICT METERING AREAS IN WATER SUPPLY NETWORKS

3.1 Definition

Water distribution networks are used to supply drinking water to consumers (like households and businesses). They usually consist of complex nonlinear combinations of hundreds or thousands of nodes that include water reservoirs, pressurization stations, water tanks and consumers, with all linked by pipes, pumps and valves. Around the world, the water distribution infrastructure is experiencing aging and increase in failures (including pipe bursts). Because of these issues, concern in drinking water quality is also rising. Also the size of existing networks may pose inefficiency in system operation. To manage a huge complex like that and to quickly detect anomalies, an efficient strategy is needed, and one working solution is to hydraulically divide the network into smaller more manageable sections with valves. These separated areas are called District Metering Areas (DMAs) and are presented in Figure 4. (Allen, M et al. 2011; Hajebia, S et al. 2014)

In a DMA usually at least the start and end-/consumer points of each section are equipped with flowmeters and possibly pressure meters. All water flowing through a DMA is metered and with further analysis of the data, the state of the network is defined. Also water quality measurements may be implemented in cases where the water is at risk of contamination, reactive monitoring may pose serious health issues or water quality sampling is not efficient enough.
(Allen, M et al. 2011; Hajebia, S et al. 2014)

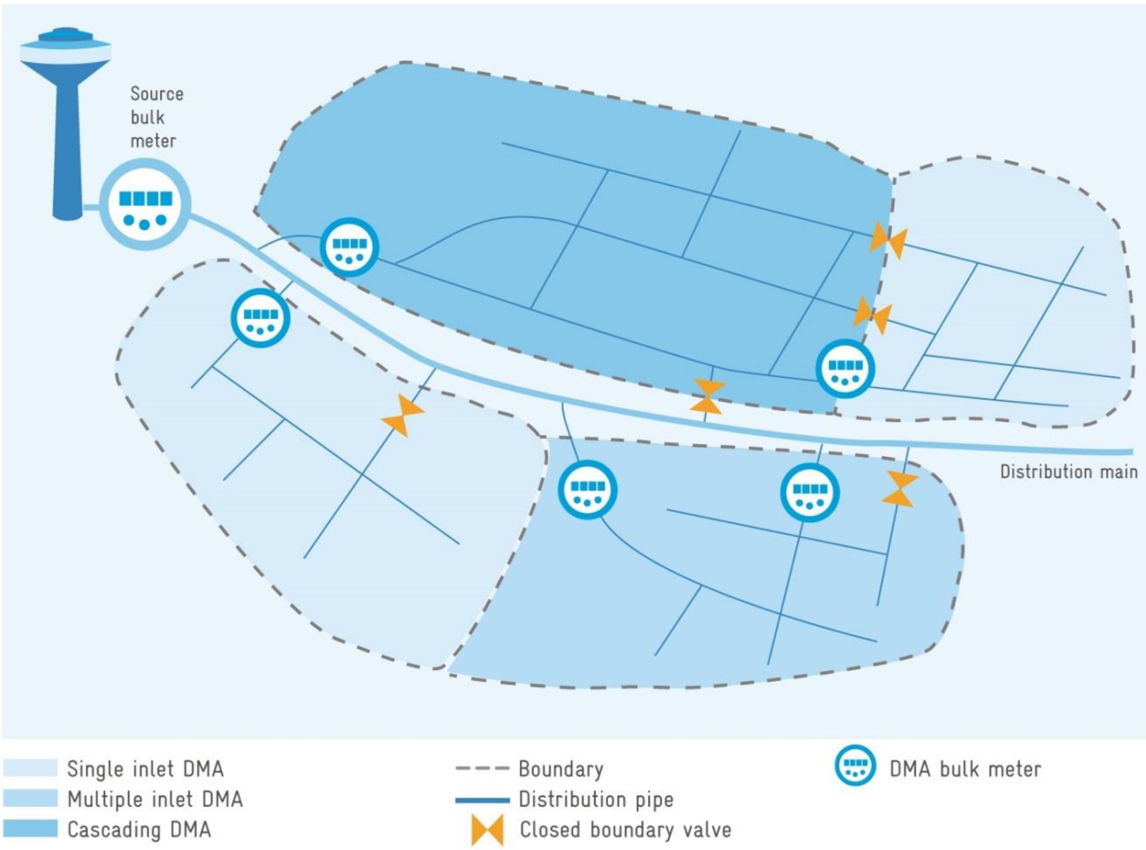


FIGURE 4 Typical layout of a DMA in a water distribution area (waterloss-reduction.com) based on the models in Farley, 2001. Leakage Management and Control. World Health Organization.

Almost everything in the DMA can be measured. With measurements, a hydraulic model can be created to present a default state overall picture or a current state overall picture of the network. It can be used to outline a distribution area in quality anomalies or to detect the appearance of singular leaks or to determine the amount of background leakage across the pipelines.

3.2 Reduction of Non-Revenue Water

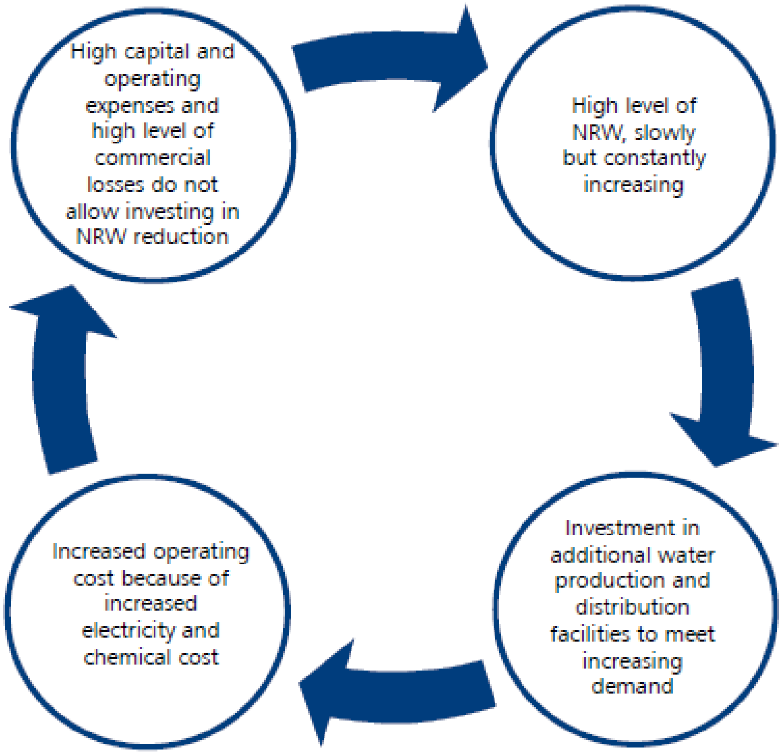
Non-Revenue Water (NRW) is defined simply as the difference between water pumped in the water supply system and the water that actually reaches the customer; hence it is water that will not create revenue. The definition is developed by International Water Association (IWA) and it is divided into three categories

- Most typical reasons are called physical or real losses. In these cases, the increase of NRW is caused by leaks in the pipe network and overflows in the water reservoirs.
- Another type of losses is called apparent or commercial losses and is usually caused by theft or measurement inaccuracies.
- The third type of losses is unbilled authorized consumption, which includes water used by firemen and other sources where the water is provided for free.

(Frauendorfer & Liemberger, 2010; www.iwa-network.org; Ditcham, Steve)

Another notable issue with NRW is to check the metering equipment as many types of meters will either begin to under-read or over-read quantities over time. Under-reading meters will suggest a greater NRW and have a negative effect on the revenue, whereas over-reading meters will indicate the total sum of water being consumed be equal or greater than is entering the network, hiding possible leaks and other NRW factors. Therefore, active calibration and maintenance of equipment is important in a realistic NRW evaluation. (Frauendorfer & Liemberger, 2010; www.iwa-network.org; Ditcham, Steve)

High levels of NRW cause difficulties in meeting consumer demands, drop in water utility performance levels and bigger losses are met when trying to keep water at affordable prices while a large portion of water yields no revenue. As the water of the utility company is lost, its costs increase, sales decrease and it may enter an endless cycle in which both costs and NRW increases as seen in Figure 5. (Frauendorfer & Liemberger, 2010.)



Source: R. Liemberger.

FIGURE 5 The Vicious NRW Cycle. (Frauendorfer & Liemberger, 2010.)

Substantial NRW can even lead in health risks when supply becomes intermittent and causes interruptions and breaks in supply. The water can be contaminated by ground water or even by sewage if they have access to supply network during these low-pressurized periods. All the problems caused by high levels of NRW also cause low willingness to pay for supplied water, what can further sustain the vicious NRW cycle. (Frauendorfer & Liemberger, 2010.)

In the modern world, NRW usually accounts for 25 to 50 per cent of the total water supply. In some cases, even as high as 75 per cent NRW has been recorded. Reducing the NRW has many benefits in addition to water preservation. E.g. as NRW is reduced and less water is pumped to the network, the network utility also uses less energy. Also as there is less leakage that flows into sewage, less sewage water needs to be treated. Fewer leaks also mean less water contamination risks. (Hvilshøj, 2015.)

The most important setting to reduce NRW is to set up DMAs which include data gathering, analyzation and automation. In some instances, more efficient pressure management based on automated data analysis has show drops in average system pressure up to 20 per cent. In addition, through a better management, a better overview of production, lower energy consumption and awareness campaigns also the water consumption itself has lowered. (Fantozzi, 2009; Hvilshøj, 2015.)

3.3 Continuous measurement in water supply networks

A requirement for a DMA is to utilize continuous measurements in the network. This way the status of the network can be defined, and possible anomalies can be found. This consists of hydraulic and qualitative measurements that are presented below.

3.3.1 Flow metering

One of the fundamental parts of a DMA is the metering of water flow rate in the water supply pipe network, usually presented in cubic meters per hour (m^3/h). Comparing the values of two different flow rate sensors on both ends of the pipe (metering nodes) reveals if there are leaks between them (assuming the meters do not over- or under-read). This is carried out by utilizing the principle of conservation of mass, which means that all mass of water that enters the pipe should be equal to what exits from the other end:

$$\sum_{j=1}^{pipes} Q_j - D_M = 0 \tag{1}$$

where Q_j is the entering flow from the *j*th pipe and D_M is the amount of exiting flow. This equation is implemented in all nodes of the network (Misiunas, D et al, 2006).

If the flow rate is lower at the end of the pipe than is pumped there, presence of a leak is a possibility. This may require some data processing, however; in some cases, the measured flow rates may include fluctuation, so it is not useful to compare the real time readings of the sensors, rather, an average is needed for the differences to be caught. (Misiunas, D et al, 2006).

3.3.2 Pressure metering

Continuous water pressure readings in the water supply network pipes are also the most basic and used type of continuous monitoring in the water distribution networks, usually presented in bars (1 bar = 100 000 Pa). Because the pressure levels are always kept at steady levels in the pipeline when it is in normal, active state, even by only looking at the measured real time values, the operator can observe whether the system operates normally. Pressure monitoring is also used in pump control: the pump's PID-controller calculates the correct frequency for the pump via the wanted level as the control setpoint. (Lehtola, 2016; Water-M user survey)

3.3.3 Quality metering

Water in water supply networks must always fulfil qualitative (pH, conductivity, turbidity, taste, smell etc.), chemical (concentrations of arsenic, fluoride, cyanides, lead, nitrites, polyaromatic hydrocarbons etc.) and microbiological (presence of *Escherichia coli* and intestinal *enterococcus*) requirements set by authorities for it to be allowed for distribution. Quality is not usually measured in the distribution network DMAs mainly because most quality measurements are made at the facilities before the water is pumped into the network. However, leaks or other unwanted events in the network can cause unwanted quality changes that are only detected via reactive methods. This may lead into longer periods of low-quality water distribution compared to proactive methods by real time measurements. Currently constantly cheapening meters enable extended quality measurements, for example, conductivity metering is a cheap method of detecting whether the water in the network has something it should not have (like impurities) and if it needs further analysis. It is also currently gaining more support in including it to DMAs. (Finlex)

Chemical and microbiological measurements are usually made by certified laboratories and are made by sampling from sampling points in the network. This can pose problems in measurement accuracy, when the sampling frequency is too small, it can also pose risks when anomalies happen shortly after the water is qualified as safe. While automatic continuous measuring could provide a more comprehensive status of the water quality in the network, measurement confirmation can be problematic in these cases because authorities often require certificates on the measurements and issues can rise in accurate calibration that may make the validation difficult. Combining both sampling and automated monitoring, the most effective way for water quality validation in the water supply networks could be provided. (Water-M user survey)

Continuous quality metering can be carried out using the same principle as in hydraulic measurements, only sensors are different. More complex attributes like alkalinity that require laboratory-analysis cannot be measured through sensors, however, new technologies are being developed continuously, and innovations like automated bacterial measurements arise from time to time that could be used in the future to establish all-encompassing DMAs (Hakalehto, 2016).

3.4 Present state of district metering areas in Finland

Until today, efforts in water supply networks have been mainly concentrated on building and expanding new network. This has lead into problems considering reorganization debt, which forms from network that doesn't meet modern requirements for water supply networks. This can result from rapid expansion or because the pipeline has been built from low-quality materials rather than cast iron. The old network may also have been built without exact mapping information which can lead into inadequate location, size or material information (Mustonen 2010, 5). All this has lead into water supply networks suffer from somewhat partial to considerable neglect concerning renovations and general condition management. It has also fallen clearly behind in maintenance compared with power-distribution networks. A huge portion of the network is old and suffers from an inadequate condition, especially in large cities like Helsinki, Turku and Tampere. Centers of big cities may have pipelines as old as 100 years. (Luomanen, Hanski and Oulasvirta 2013.)

DMAs mostly have had only minor roles. The water networks themselves have little hydraulic monitoring and even less quality monitoring. However, the interests have risen during the last decade. Monitoring is practiced mostly by reactive methods, which practically means that noticeable hydraulic or quality changes are reported by consumers, when the substandard-quality water has already reached the customers and the area of its effect has grown to full size. Also periodic reporting practice is in use in quality monitoring, however, it cannot be held as an automated continuous measurement convention because its measuring frequency is too low for rapid detection of changes in the system. (Water-M user survey)

In the next 30 years, household water consumption is estimated to rise only about 1 per cent (about 6 billion m^3). However, it is still necessary to invest in reduction of leaks and Non-Revenue Waters as whole, as the number of both waterworks and water supply and sewerage system stations is reducing and the same time the amount of consumers is rising. Especially municipal water supply stations are taking possession of small economically beleaguered waterworks' cooperatives which have difficulty to keep up with standardized water quality standards and have no resources to renovate their water supply network. This creates pressure to invest in water saving programs and optimization of networks and systems. (Kujala-Räty et al, 2008)

3.5 Possibilities and challenges

In the last years the interest and need for comprehensive monitoring systems and proactive control systems has become greater. Some solid problems can be separated which could be answered implementing a comprehensive DMA:

- Control systems and various monitoring and measuring systems are usually segregated which poses problems in complexity and increases costs in upkeep of such systems
- Automated water measuring systems are becoming more common in households and implementing them in the monitoring system could provide an efficient way of automated billing and expanding the DMA
- Quality measurements are mostly made by manual sampling and certificated laboratory analysists. Continuous monitoring could lower the measurement uncertainty and increase proactivity
- Computational values of data analysis can quickly detect and localize leaks and other anomalies in the network
- Merging automated measurement readings in electrical-, district heating- and water supply companies could further advance the proactivity in system malfunctions in all these fields
- Standardized interfaces would make the implementation easier especially in scalable systems

Most challenges analyzing the hydraulic characteristics pose from the vast spectrum of different types of structural and situational nature of the water supply networks. For example, the consumption rates differ drastically between multitudes of elements, which can be:

- The consumption profiles may differ greatly between cities and rural areas
- The consumption rates usually differ drastically between households and industrial facilities
- Water supplying methods may have effect on the hydraulic behavior and hardware optimization like in the case in Figure 6
- DMAs with monitoring only at inlet and outlet points have less precise leak localization than in DMAs with metering points across the network
- Branched and looped sections of water supply networks behave differently
- Additional water reservoirs and pump stations have their own effect on the system
- Poorly planned or old networks can have problems with stabilization
- Incomplete DMA or defective sensors can render the DMA partly or completely ineffectual (especially in DMAs with only inlet and outlet metering points)

(Allen, M et al. 2011; Water-M user survey; Lehtola, Markku, 2016)

Other challenges in implementing a comprehensive continuous measurement system is its cost in building and maintaining such a system, that includes:

- The cost of instrumentation and its installation and upkeep
- Costs in data collecting
- Costs of data transferring equipment and transferring itself (like broadband costs)
- Server costs in data storaging
- Costs in building analyzation tools and methods for automated systems to use.

The costs are dropping currently however, when open source programs are being published, demand for such systems is rising and the development in measurement instrumentation is advancing. Some other factors affecting the drop in costs include improving battery technologies that extends the lifespan of measurement points while newer meters can preserve their calibration longer. Also broadband costs are currently low and are expected to drop further while the global demand for faster and better services is rising. (Water-M user survey; Lehtola, Markku, 2016)

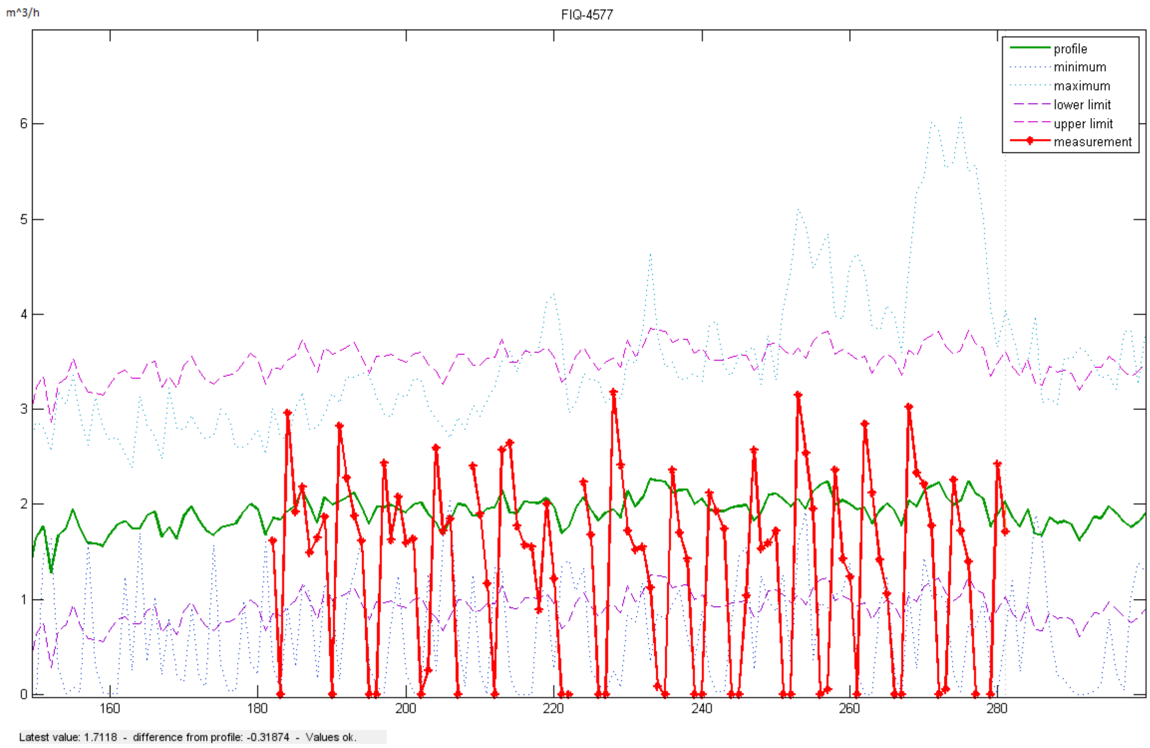


FIGURE 6 Example of a pumping that causes heavy fluctuation to flow rate. Red graph presents the measured values in real-time (flowing from left to right))

However, data profiling offers some remedy in identifying problems. While the data is collected and profiled rather than calculated, all the affecting variables are essentially inside that data. This eliminates some of the following drawbacks in calculated models:

- If calculations are not verified by measuring, they can be only considered as approximate and instructional
- When something is altered in the system, all the calculations must be redone
- Natural decay of the equipment is very hard to take into account
- Calculations need regular updating
- Calculations always have an error margin. The more calculations are based on previous calculated values, the error margin grows exponentially
- Calculations are prone to a human error

For example, a consumption model can be formed from gathered flow rate data. This way, waterworks and cooperatives may include automatic billing system in their services. For more advanced systems, this data can be used to make bigger consumption models for distribution areas, like towns or sections of cities. This way a model can be formed and it can be utilized for hardware optimization. A consumption model of a distribution area consisting mainly of households shows clear persistent form, and it can be used to prepare the facilities, like activating more pumps when the water consumption is estimated to rise, or to partly adjust their PID-controllers to keep steady pressure levels without unnecessary stress for the system.

The automated profiling is formed from continuous data and doesn’t involve any complex calculations. While automatically generated profiles need reforming too, the older complete profiles, which have represented the real situations at previous times, can be compared to the current profiles to reveal the real differences in the system caused by instrumental changes or long-term deterioration. (Analysis from the data; Lehtola, Markku, 2016; Water-M user survey)

3.6 User survey of needs in water supply network monitoring systems

In DMAs, it is important to first map the needs for the system before it is implemented. Because of the diversity of possibilities, options, adaptations and automations, the system can quickly become too massive for the needs of the network. It is important not to include any unwanted or pointless elements to a system as it increases costs from both software and hardware upkeep and implementation. A more welcome approach is to answer the needs of the water supply network DMA, construct the DMA based on those needs, and leave room for possible future implementations. For the development of automatic DMA monitoring in the Water-M project, a small scale user survey of water utilities' technical personnel was made to map the primary aims for the development. The principle was to separate the objectives in three categories that were: The primary objectives that must be included in automatic DMA monitoring systems according to water supply network proprietors, secondary objectives that have not that much demand but may be included, and completely optional objectives that may be included at later stages if the need arises.

The monitoring software for a DMA was customized according to the results, which indicated mainly that hydraulic characteristics were the most important ones to monitor continuously. However, quality monitoring is necessary too and may be included in a comprehensive monitoring system in the future. This in mind, the program was also included with an option of determine static single-value limit values that may be more useful in such measurements.

3.6.1 Execution

The user survey was directed to owners or technical personnel operating water supply networks which consisted of waterworks and cooperatives. Most of the answerers were big operators but a couple smaller communities were included, too, and the shape of answers did not differ greatly when considered in objective-oriented manner. The user survey consisted of a number of categorized questions, and the idea was that the interviewee prioritized the importance of possible features that could be implemented in a DMA. In addition to that, a more specific phone interview to further clarify the answers was included in which some of the participants agreed on. However, because of the reluctance of phone interviews due time restrictions, and the net information that was gained in addition to the question form itself was not significant, the phone interviews were not further executed after two cases. Also one personal interview was carried out in which the needs were analyzed in a more in-depth manner.

A total of eight participants agreed to answer the user survey, two of them agreed to be further interviewed by phone and one participant was interviewed personally. The list of participants was:

- Kuopion vesi
- HSY (Helsingin seudun ympäristöpalvelut)
- Kangasalan vesi
- Tampereen vesi
- Inarin lapin vesi
- Ylivieskan vesiosuuskunta
- Ylä-Savon vesi
- Äänekosken Energia Oy

3.6.2 Results of the user survey

The results were pretty straightforward without depending much on the size of the operators. Not much monitoring was executed in the network itself. In the bigger facilities, the water station itself had quality monitoring before the water is pumped into the network. Pressure monitoring combined with pumping and water level monitoring in the water tanks/reservoirs is also always present. Also consumption monitoring in total of what is pumped in the network is practiced, but often nowhere else. Smaller water supply networks were very interested in pilot-scale DMAs, but costs were the biggest preventing factor.

The prioritization of needs for automatic measurement in water supply network DMAs was executed by making the user choose between following options:

- "Very important" that counted towards 100 % of necessity in a DMA system in water supply network
- "Quite important" that was counted towards 50 % of importance, and
- "Not that important" that was counted towards 0 % to present that it is not important cost-efficiency -wise right now.

According to the results in the status illustration as seen in Figure 7, modeling is one strong aspect of the DMA. And it can be used in basic modeling of the network that is the basic structure of the pipe network or computative modeling e.g. with EPANET. Real time modeling is the core of DMA and can be used in various automation-related tasks. Hydraulic monitoring is widely required, however, quality monitoring is nod needed as most quality analysis is made during water treatment and via sampling and reactive methods.

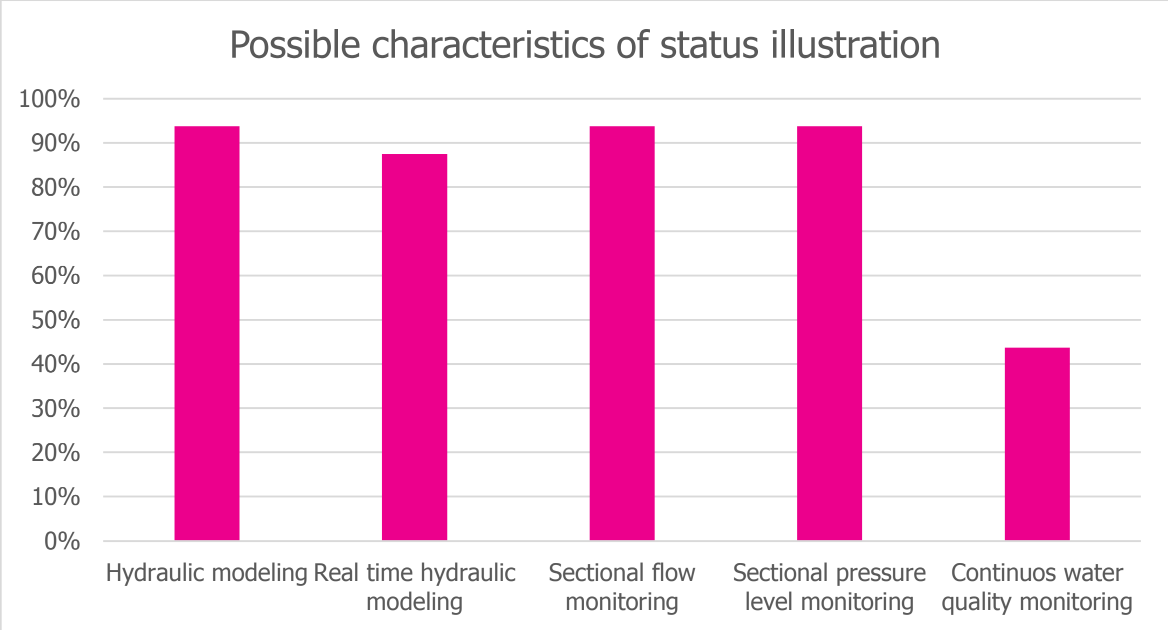


FIGURE 7 Comparison of need in different characteristics of status illustration in a DMA

In hydraulic monitoring, leak detection was unanimously the most wanted feature as seen in Figure 8, followed by detection of other anomalies and measurement accuracy confirmation. Pressure shock and flow direction monitoring were not as desired, and may be more important at future installations.

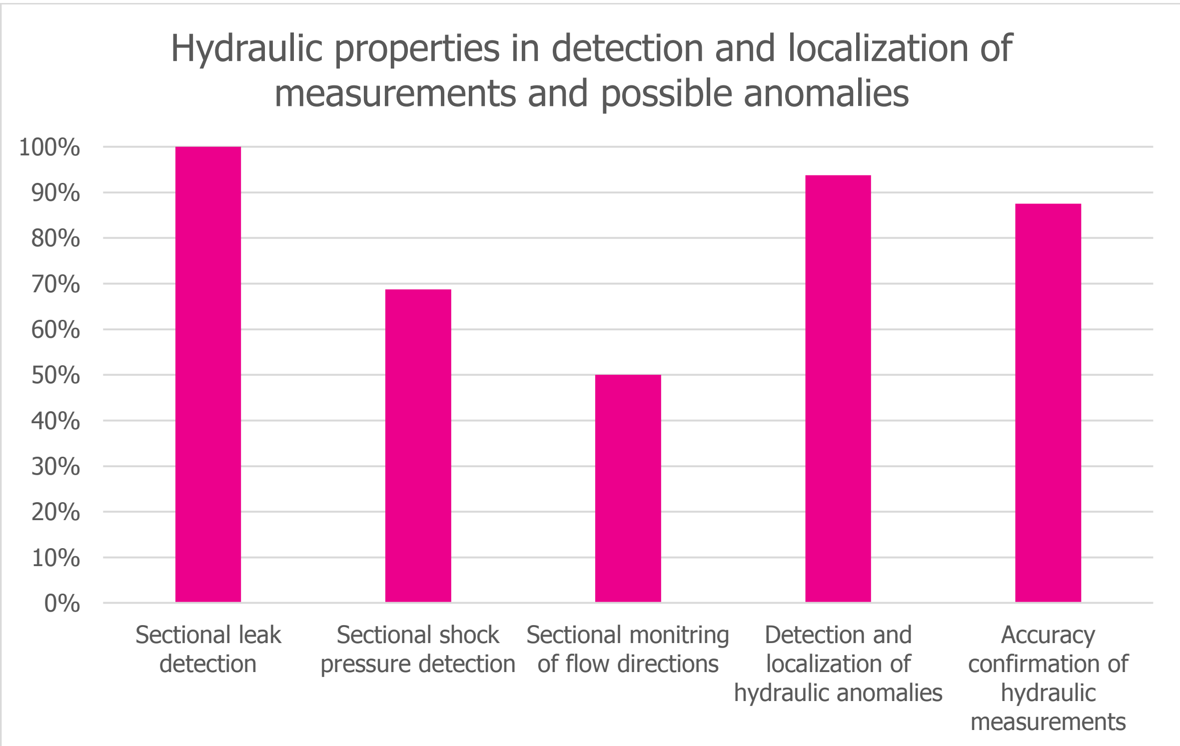


FIGURE 8 Comparison of need in different hydraulic properties in detection and localization of measurements and possible anomalies in a DMA

As seen in Figure 9, quality monitoring didn't score as much demand (mainly due cost-effectiveness and its implementation outside of the network was seen as sufficient), however, it might be more relevant at later times, when the instrumentation becomes cheaper and its implementation can be made straight to an existing DMA.

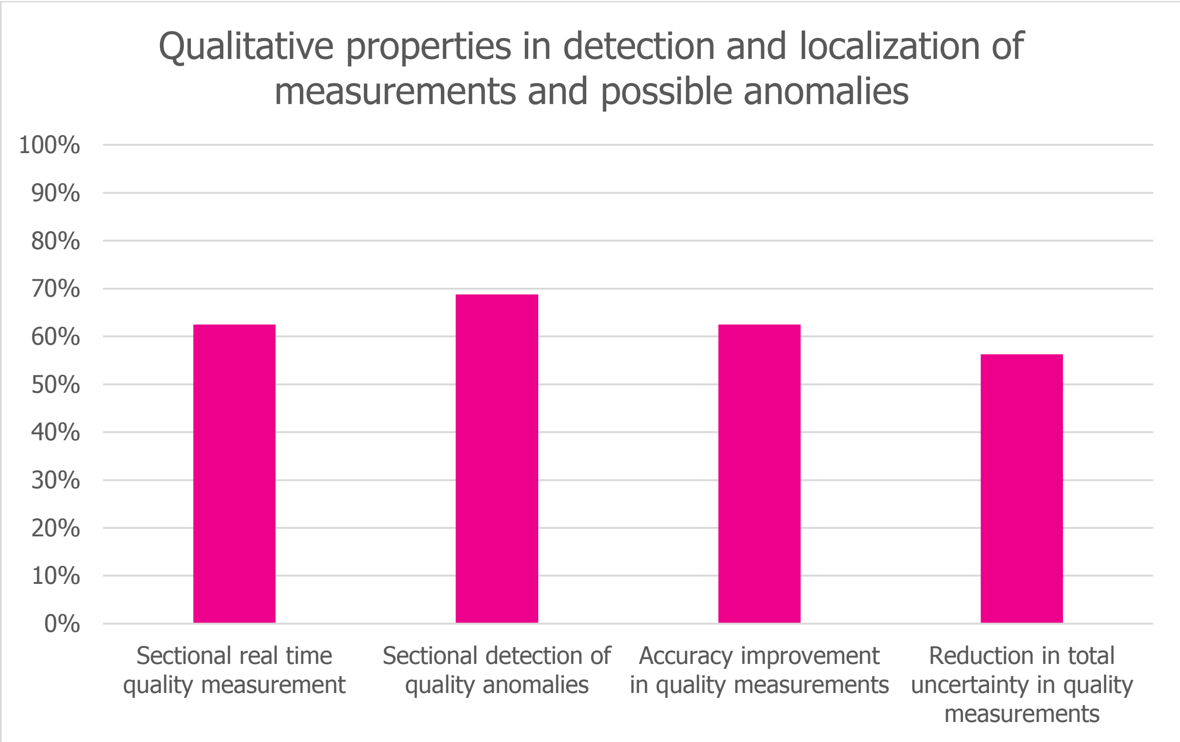


FIGURE 9 Comparison of need in different qualitative properties in detection and localization of measurements and possible anomalies in a DMA

In automation, the most desired features are automated alerts made by the monitoring system and automated control as seen in Figure 10. Usage forecasts were not considered as important, as water suppliers usually have good predictions based on experience. Energy use forecasts were not that relevant, as it is one aspect that usually cannot be managed separately.

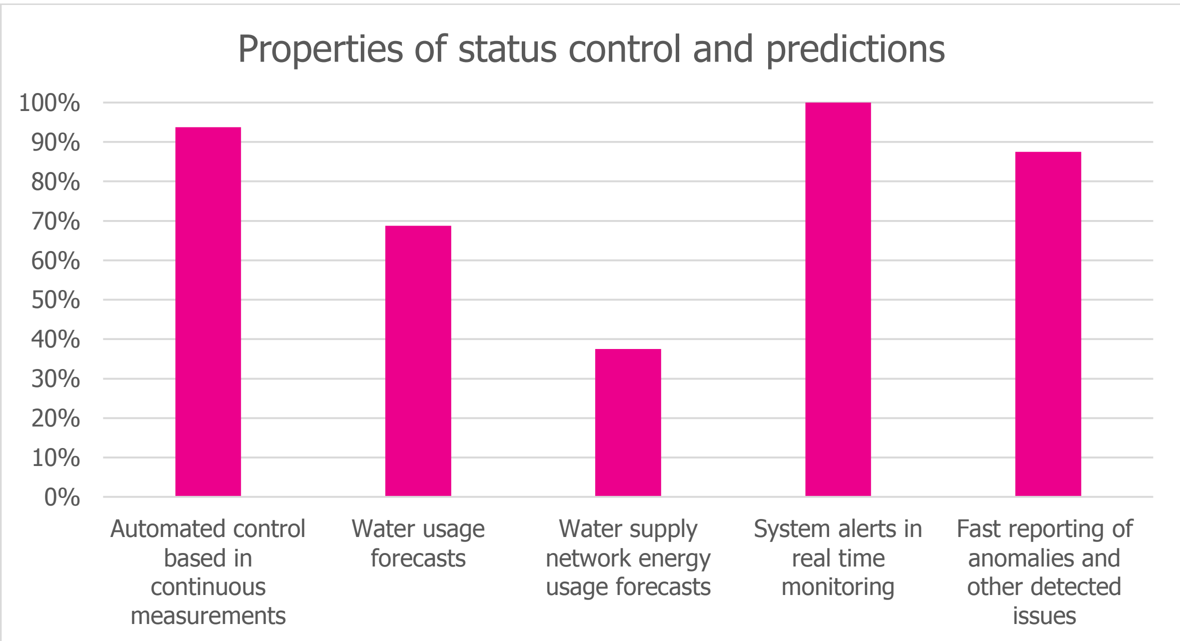


FIGURE 10 Comparison of need in different properties of status control and predictions in a DMA

All the other properties were considered useful and were welcomed in DMAs as seen in Figure 11. The merging of separate measurement systems got positive feedback because of its potential in lowering costs in maintaining many different monitoring systems and their interfaces and overall simplification of the system in whole.

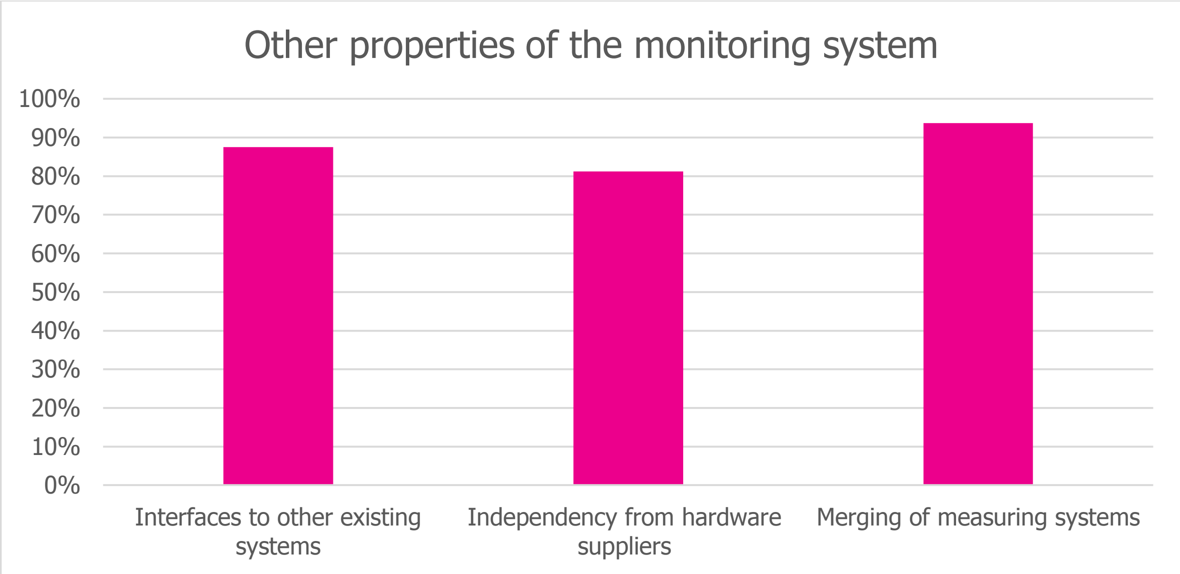


FIGURE 11 Comparison of need of other properties of the monitoring system in a DMA

4 DMA DATA TESTING ENVIRONMENTS

For development and testing of dynamic monitoring system, two systems were utilized. The first was the Savonias own testing system, the other was Vehmersalmi district metering area.

4.1 Savonia Pilot Water Supply Test Network

Savonia University of Applied Sciences has a water supply test network for various testing purposes. The network consists of three separate loops which are connected with measuring and monitoring equipment and are operated by both adjustable valves for regulated output flow, and solenoid valves for the open/closed states of the pipes (which also have possibilities for automated programs).

The sensors measure and send data to the database at one second interval. The data is saved into the database by using the Savonia Measurements System Sami and can be further analyzed with analyzation tools and programs.

The network also has quality measurement for pH, turbidity, thermal conductivity and UV-absorption. It has options for making pressure shocks and circulating the water in different pipes and simulating realistic water consumption (e.g. households fluctuating water consumption levels during a 24-hour cycle).

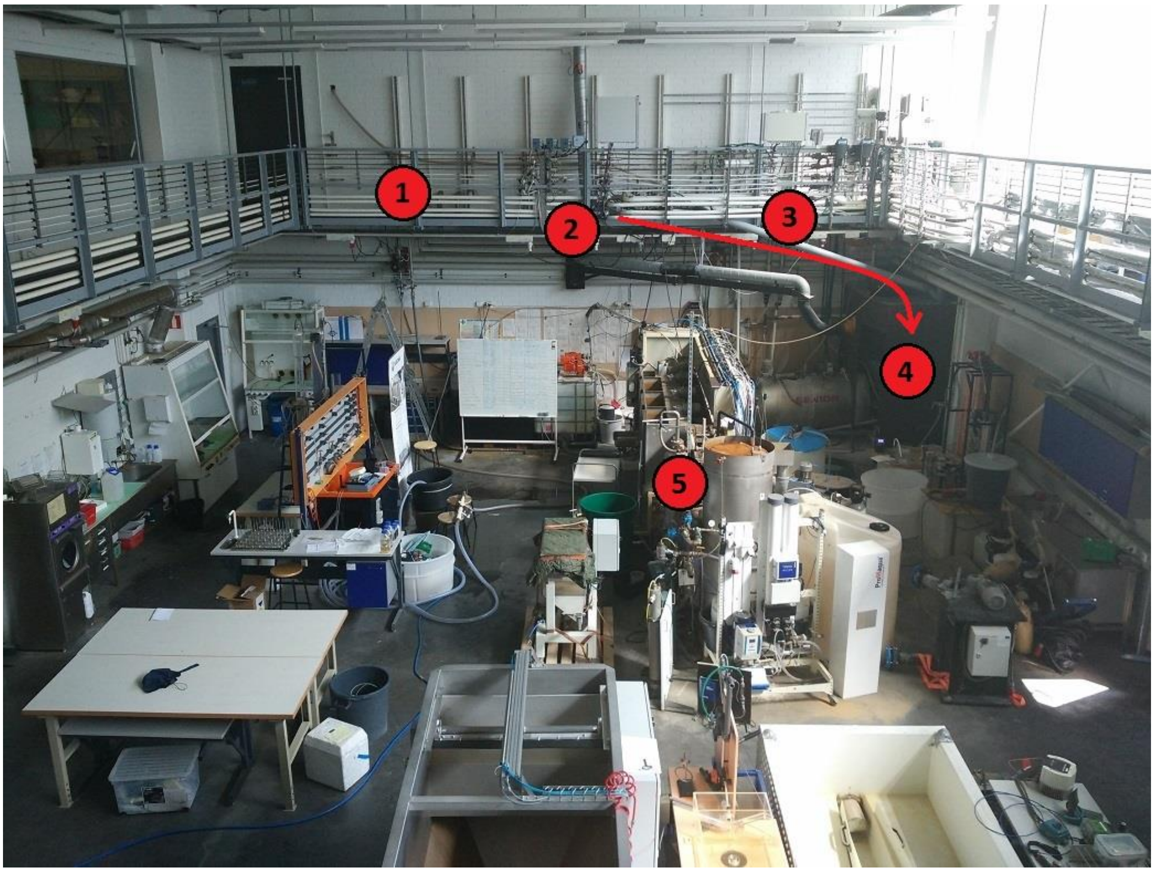


IMAGE 1 Savonia Test hall

In Image 1, the relevant equipment for this thesis are marked by numbers. These represent the following parts:

1. The Pilot Water Test Supply Piping that loops around the test hall multiple times
2. One of two points of water output valves (The other point is across the hall). It includes both outputs for water quality testing, valves for leak simulation and a solenoid valve combination for household water consumption simulation.
3. Quality measurement equipment
4. A sewerage tank in which all the leaks and consumption simulation waters are gathered
5. The Pilot Water Treatment Plant for making surface water suitable for the network

The arrow represents the flow route from the first outflow valve point to the sewerage tank, the water flow similarly from the other point of the network. Both the sewerage tank and the Pilot Water Treatment Plant pump the water to the main water tank.

The 600 m of pipeline network consists of three different kinds of pipes:

- 2 x 100 m copper pipeline (outside diameter 12 mm, inside diameter 10 mm)
- 2 x 100 m Uponor composite pipeline (OD 16 mm, ID 12 mm)
- 2 x 100 m Uponor composite pipeline (OD 50 mm, ID 41 mm)

The pressure measuring equipment consist of digital SIEMENS Pressure transmitters. (Model: SITRANS P, Z series 7MF1564) and Ifm Electronic pt5404 pressure meters. The flow measuring equipment consist of Endress+Hauser Promag flow meter with an F-model sensor right after the main pump and for the rest of the network Burkert SE56 transmitters equipped with Burkert S055 magnetic-inductive flow-rate sensors are used.

The user may use valves to modify the pipe network to form open or closed loops or to control the flow direction in the same loop level in the network. The loops can be sealed out of the system if wished in a way that the flow is still possible in the restricted sequence (i.e. loop 1 → loop 2 → loop 3), so essentially only loop 3 or loops 2 & 3 together can be left out.

Different kinds of tests can be executed in the network. Including:

- Measurement and monitoring of pressure, flow and other variables
- Simulating a household water consumption or a small DMA
- Collection, processing, modeling and analyzation of data
- Production of visual and numerical results of behavior of the network

The loops have multiple output points possible to operate by both manual and solenoid valves that can be used for testing purposes (e.g. to simulate leakage or water consumption of a residential building)

4.2 Vehmersalmi district metering area

For data profiling also a DMA with real nodes, real consumers and real usage data was used. The data was used to form consumption models of real life situations and to make testing and conclusions in the development of the software. However, because the specifications are confidential, no further presentation of Vehmersalmi DMA is available in this thesis.

4.3 Consumption simulation

The dominant present day lifestyle of humans consists of regular sleep rhythm and mostly consistent daily work hours. This also shows clearly in water consumption rhythm as seen in Figure 12, where water consumption peak hours are during 8:00-10:00 and 19:00-22:00. Consumption is more moderate during 11:00-17:00 and lowest at nighttime.

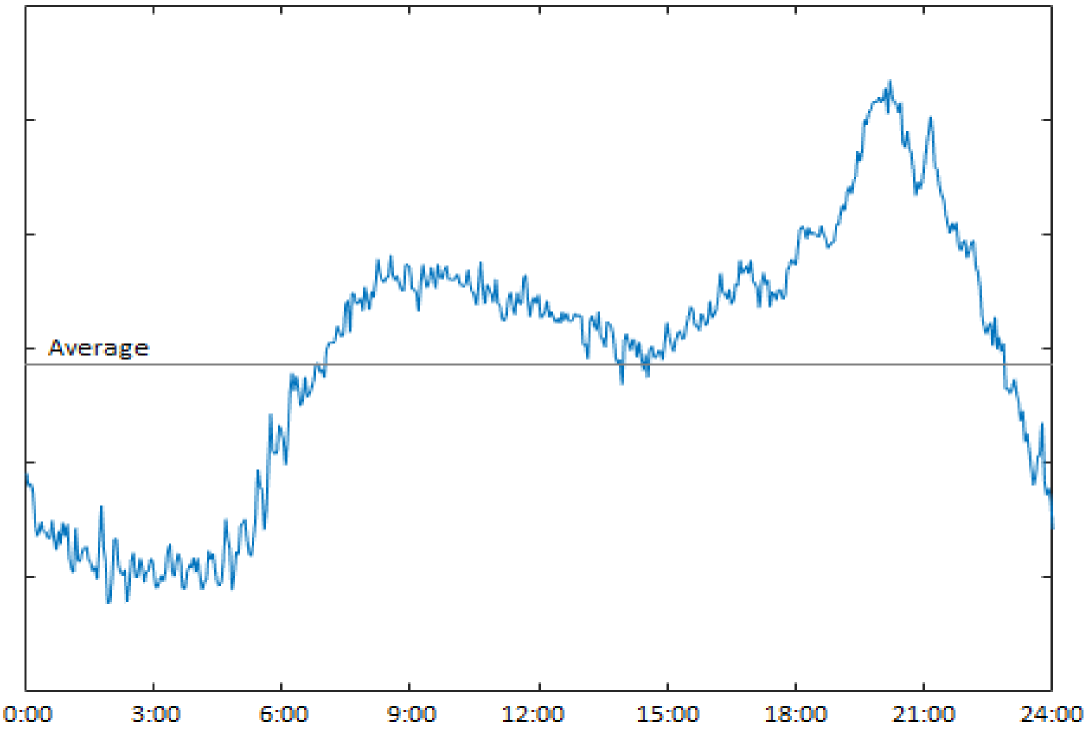


FIGURE 12 Typical form of daily household water consumption compared to its average (graph formed from Vehmersalmi district metering area data)

The Savonia pilot water supply network test system can be configured to simulate a typical household water consumption profile. With testing network and consumption simulation, a simple DMA can be simulated. This creates possibilities in creating various analysis with the data. When a consumption profile is created via simulated runs, the network can then be exposed to different kinds of simulated anomalies. The system generates alerts as it is programmed and reaction times can be measured, correctness and meaningfulness of the alerts and limit values can be polished, and all kinds of other behavioral aspects and possibilities can be tested for.

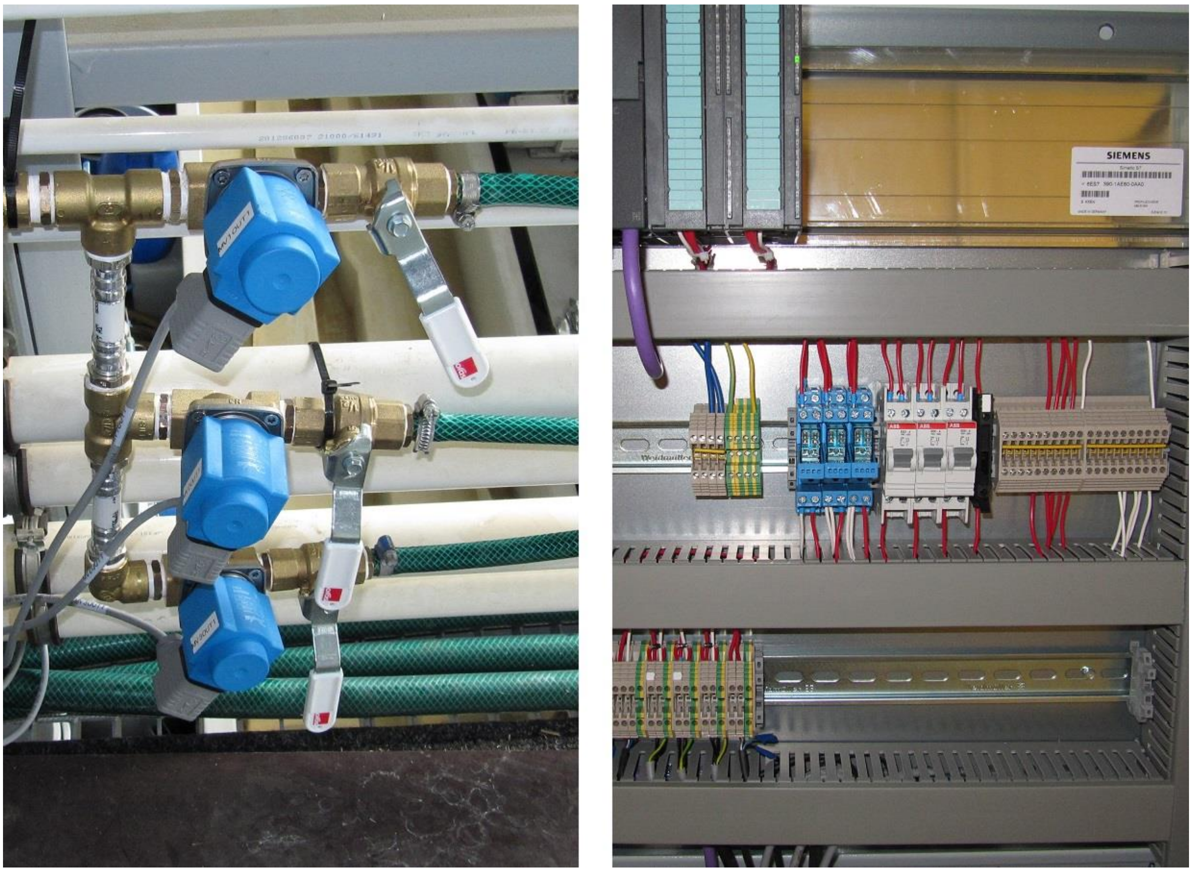


IMAGE 2 Left: Solenoid valves combined with pipe fork junction and adustable valves for simulation configuration. Right: The solenoid valve control panel for open/close manual adjustments and an option for automated program controlled behaviour (marked with number 2 in Image 1 above)

Using the simple configuration that can be seen at left of Image 2, a daily household water consumption as seen in Figure 13 can be simulated. By adjusting the manual valves in differing positions, three different flow outputs are made. By combining these flow rates by opening the solenoid valves separately or simultaneously from the control panel that is seen at right of Image 2, a total of eight different flow outputs are achieved (including the zero flow rate). Utilizing this method, a household water consumption can be simulated by setting a specific flow to a specific time interval on a daily consumption profile, like in Figure 12.

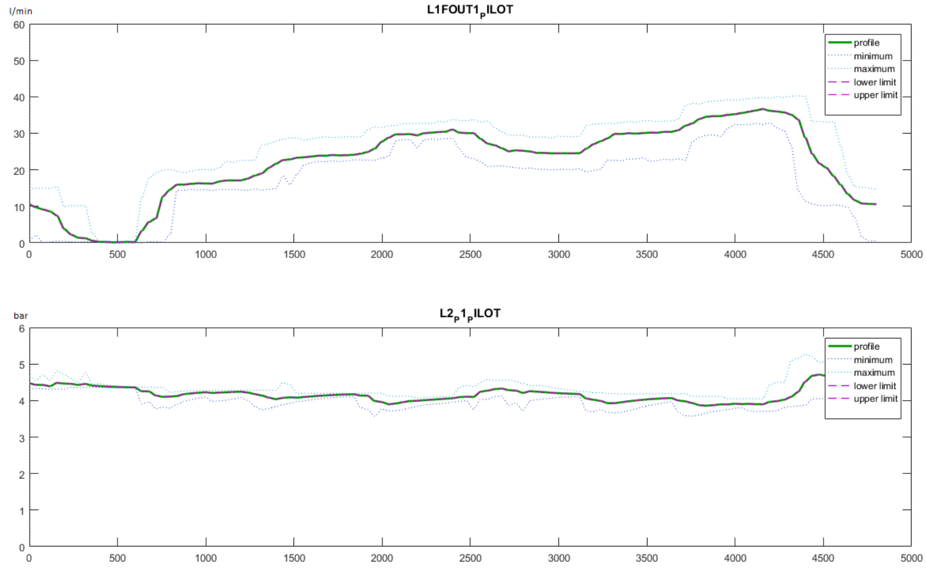


FIGURE 13 Measurement point data profile of a simulated household water consumption program

4.4 Hydraulic modeling

Savonia Pilot water supply network test system can also be used in testing hydraulic modeling by utilizing modeling software like EPANET, seen in Image 3. This can be used in simulating a simple DMA and its potency in the system. Implementing a simulated DMA in the water supply network test system, an automated monitoring software can also be tested in a DMA environment.

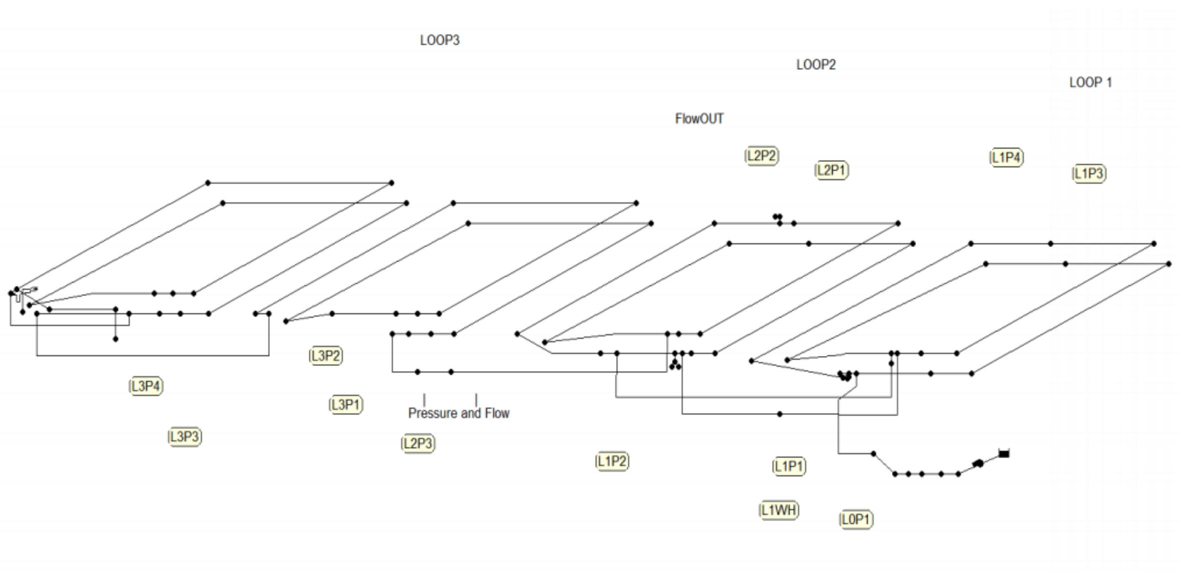


IMAGE 3 Example of EPANET model created of the network (Puurunen, 2015)

4.5 Savonia measurements system Sami

Savonia University of Applied Sciences has a measurements system called Sami (https://sami.savonia.fi). It is an open source web interface to save and import all measurement data from the database. It is a .Net Framework 4.5 application and can be run on IIS and it uses MS SQL database as data storage. It is published on the online project hosting service GitHub (can be found at https://github.com/SavoniaUAS/SaMi).

Sami interacts directly with the database in which the data is stored for further use. The data can be imported using various interfaces included in the service as seen in Figure 14. For the monitoring program written in this thesis, Sami's JSON-interface is utilized by sending a GET-request to it and parsing the JSON-data in MATLAB's numerical matrix format.

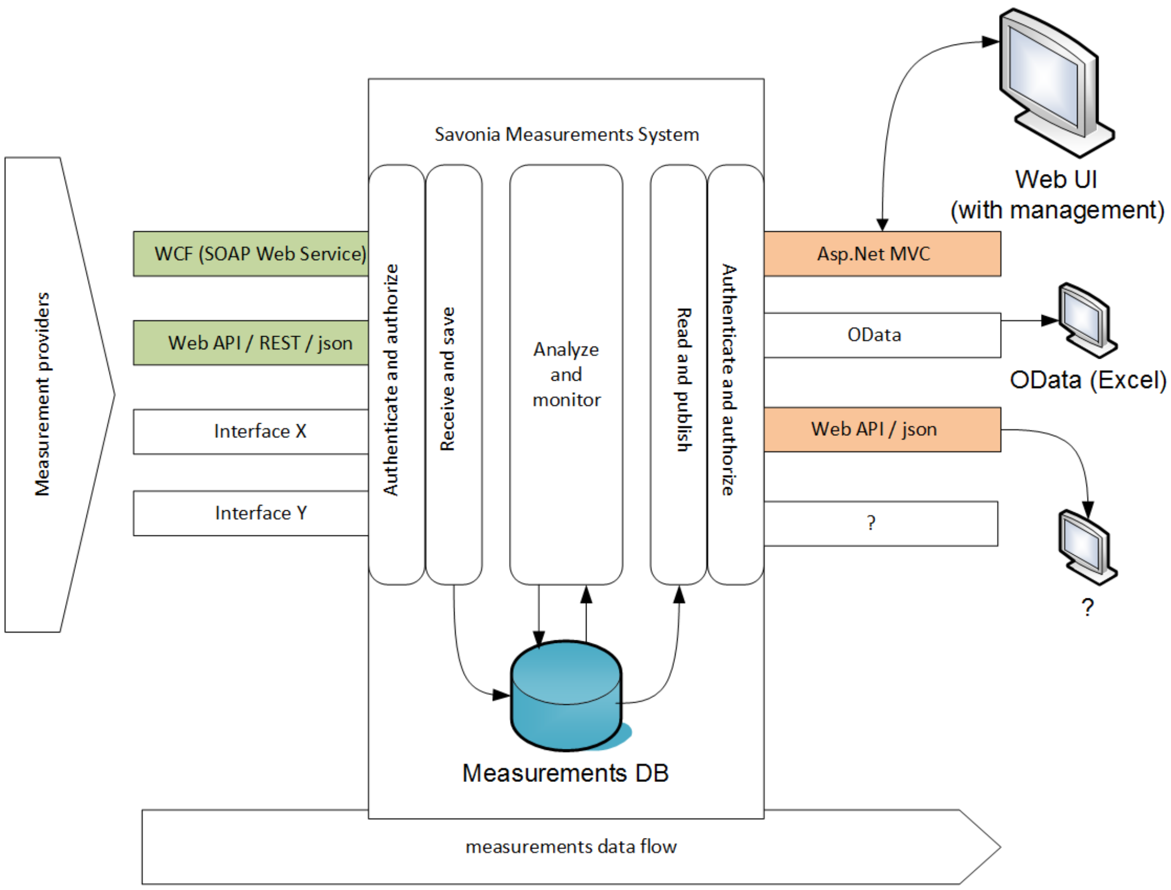


FIGURE 14 Architechture of the Savonia Measurements System Sami. (Pääkkönen)

5 AUTOMATED MEASUREMENT AND DATA ANALYSIS IN A DISTRICT METERING AREA

Currently, most of the gathered data in a DMA is usually separately analyzed by the system operator, who performs the analysis to detect anomalies based on expertise and known characteristics of the network. This can be a time consuming process, and small or long-term changes can be indistinguishable from the data. Implementing automated monitoring software that profiles the usage of all the measurement points separately, and compares the real-time data to the profiled normal state can ease the analysis process. (Water-M user survey; Lehtola, Markku, 2016)

When creating automated monitoring systems, it is often desirable for the system to alert its operators in cases when the system behavior differs from normal. This includes system-related cases like malfunctions, power failures, sensor errors etc. It also includes the characteristics being monitored, like when the values are too high or low or some other anomalies appear. For the system to recognize these unwanted changes, limit values must be set for the measured values in which the measured values are compared. When the system then detects a value that exceeds these limits, a corresponding alert can be sent to the operator.

5.1 Modelling and profiling the normal state of water supply networks

Visual modeling of the data is an excellent way to observe hydraulic behavior in the network. These models can be also used in prediction of future states of the system and/or comparing it to real-time data to make deductions of the current state. When the normal-state profile is created from the data (with sections of anomalies removed from the data pool) the precision of the profile can be further improved. This can be carried out by comparing the new values to the profile and if the values follow the shape of the profile according to set parameters such as deviation, the data is included in the profile data pool. This process can also be automated and precise profiling can be set as self-learning by this manner.

It is important to note that when creating usage profiles, the real usage never precisely follows the average usage profile. All kinds of real time events affect the water consumption rates and times, and this causes fluctuation in the usage data. This leads to that the more data is available in the pool, the more precise and smooth the profile will become. As pictured below in Figure 15, profile created from two day’s data has extreme fluctuation, and while the basic water consumption form is still noticeable from the graph, the midday level is seemingly lower than is presented in the profile created from data of 120 consecutive days.

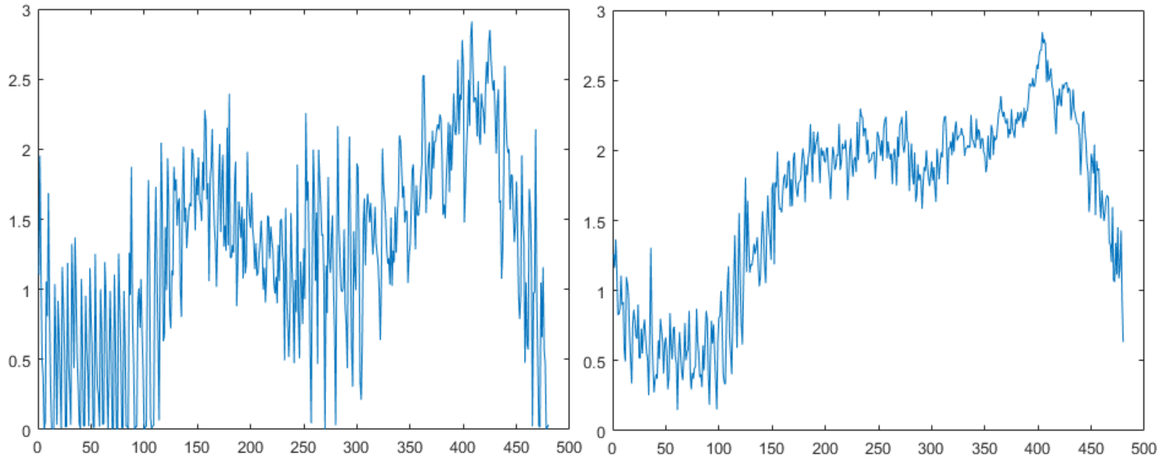


FIGURE 15 Comparison between average daily usage profiles formed from only two days (left) and 120 days (right)

When modeling large quantities of data, especially in the case of highly fluctuating variables, some processing is useful in making the visualizations more readable. Calculating the so called "moving average" is a method to create a series of averages based on the continual data. A simple moving average is created by taking a subset of data around a specific datum index by a specified range and an average of the subset is calculated and set as the value of that index. The process is continued to include the whole data array or matrix.

Utilizing a moving average reveals the trend of the recorded data and, in addition to visualization, can be useful in making a clearer basis for forecasts and their analysis as is seen in Image 4).

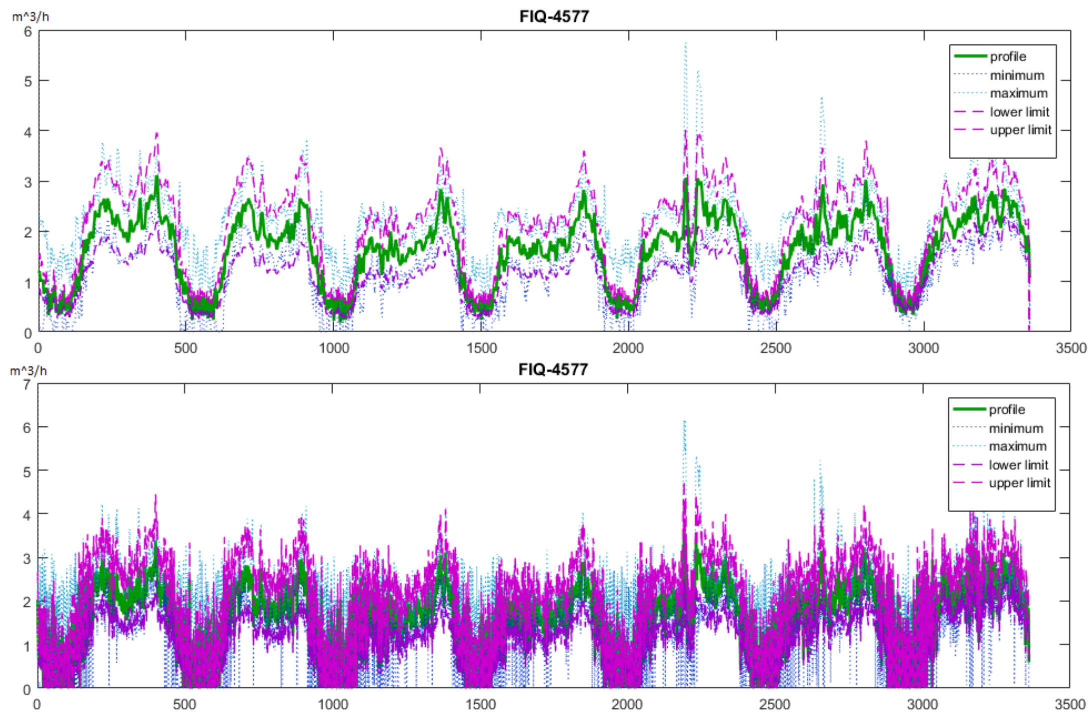


IMAGE 4 Comparison between moving average rounding and the same data profile with no rounding at all. Data represents a weekly water consumption profile of one measurement node in Vehmersalmi DMA

Other approach to determine the larger scale changes in consumption rates (like monthly or yearly) is to calculate the total accumulation of that season. That can either be calculated simply with the sum of all the values of that period, or by forming an accumulative data series of that period. This can be used to locate periods which accumulate lesser amount of total consumption or even survey the growth of consumption and to form predictions of future growth.

5.2 Outliers

The detection of outliers is required to maintain a reliable data set. In addition to singular measurement errors or other malfunctions, it is also good to exclude contextual outliers from the data in hydraulic monitoring. For example, when forming a weekly consumption profile, it is necessary to separate various anomalies like pressure drops caused by power outages (Figure 16) from the data. Also different seasonal holidays stand out from regular days and affect the consumption profile. This can be averted by excluding the days from the data pool and creating a different profile separately for them.

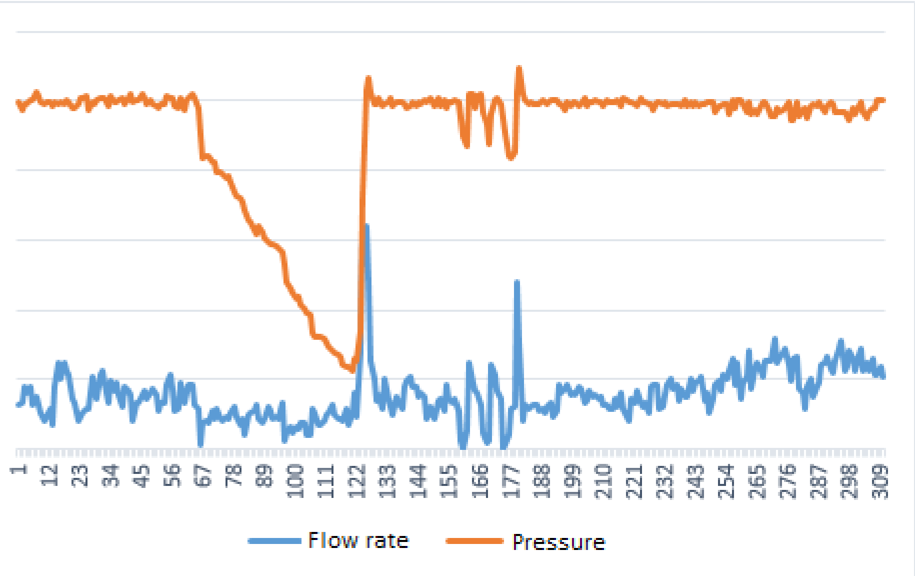


FIGURE 16 Example of an event when a power outage causes a pressure drop in the network. Including this data in the profile would cause the values appear lower than they should be in normal state at this time interval.

5.3 Automatic alarms and hardware automation

Compared to the regular data logging and monitoring software which only record and visually represent the data, automated monitoring software can be assigned to execute certain functions based on the monitored data. For example, when the limit values are exceeded, the automated monitoring program has to know how to behave in such circumstances.

The exception responses in automated monitoring programs can be one or a combination of the following examples:

- Try to analyze the cause of the problem
- Notify the accountable operator of the system
- Adjust the elements affecting the measured variables
- Isolate the problematic section from the complex
- Halt the process

While automated systems often operate on feedback loops, this is not always an option when the situation needs to be analyzed by a person or it is impossible to alter the prevalent situation, especially in more complex systems, where such measures could cause harm to the other sections of the process. In these cases, the program calls another function that alerts the system operator via a preferred method (usually by email or a text message depending on the urgency of the matter).

5.4 Challenges in interpretation and analysis of hydraulic data

Data interpretation is always a challenge in determining events in automated systems. Some challenges can arise in recognizing and separating the anomalies measured from the measurement errors, measurement fluctuation and noise.

In continuous measurement, one of the challenges lies in the recognition of normal state data from anomalies in the system. This can be answered either by complex calculations based on the characteristics of the system or recording a data-based profile which indicates how the system behaves in normal use. This profiling does not necessarily include any complex calculations and rather just records and forms a profile that indicates how the system behaves in the normal state.

Knowing how the measured system works is still necessary. As for example, the nighttime fluctuation can be heavy within some pumping systems when the pumps have only modes to be either fully on or off. This creates the flow rate to jump up and down rapidly during the night. If the operator is not aware of this, it may cause unwanted alarms if the program is not set up correctly or wrong methods are used in defining the dynamic limit values.

6 ADVANCED MONITORING SOFTWARE

For this thesis, advanced monitoring software was written that includes:

- Importing sensor data from the database
- Pre-analyzing the collected data
- Forming data profiles and models
- Automatically generating dynamic limit values from the measured data
- Compare live feed to the profiles and limit values
- Alert the user if the limits are exceeded

For writing the software, MATLAB (matrix laboratory) was used. It is a multi-paradigm numerical computing environment that includes a proprietary fourth-generation programming language. Both the development environment and the language are being developed and belong to a company called MathWorks that specializes in mathematical computing software development. MATLAB is a suitable tool for developing various data-analysis programs for its versatility in investigating different kinds of approaches to analysis. Its basic components are matrix manipulation, data functioning and visual representation, but it is also widely expendable with modules and toolboxes like for symbolic computing and model-based design. (se.mathworks.com)

The developed software includes the following programs:

- The interface for importing Sami-JSON –data
- JSON parser for MATLAB syntax, because version 2013a doesn't have built-in options for parsing JSON-code
- A testing function for the database speed through JSON-interface
- A data-collecting software that collects stored data from database and arranges it to year-month-day-hour –based structure for pre-analysis
- A program to perform pre-analysis for the data to remove anomalous data before forming profiles
- A program to generate 24-hour profile (or similar cycle-shaped profile) either for one cycle or different days of week
- A script for generating self-made profiles (for example if profile is desired from data snippets, short cycle interval-type data or measurement frequency is greater than one hour)
- A program to visualize profiles, form specific or dynamic limit values based on the data, compare it to real-time or pseudo-real-time data from database and call alerting functions within specific conditions are met (usually when recorded data exceeds the dynamic limit values)
- A tool function to quickly trim and compute various averages from the data
- A graphical user interface for data collection, profiling, analyzing, comparing and alerting

The usage of the program follows a simple logic presented in Figure 17 below.

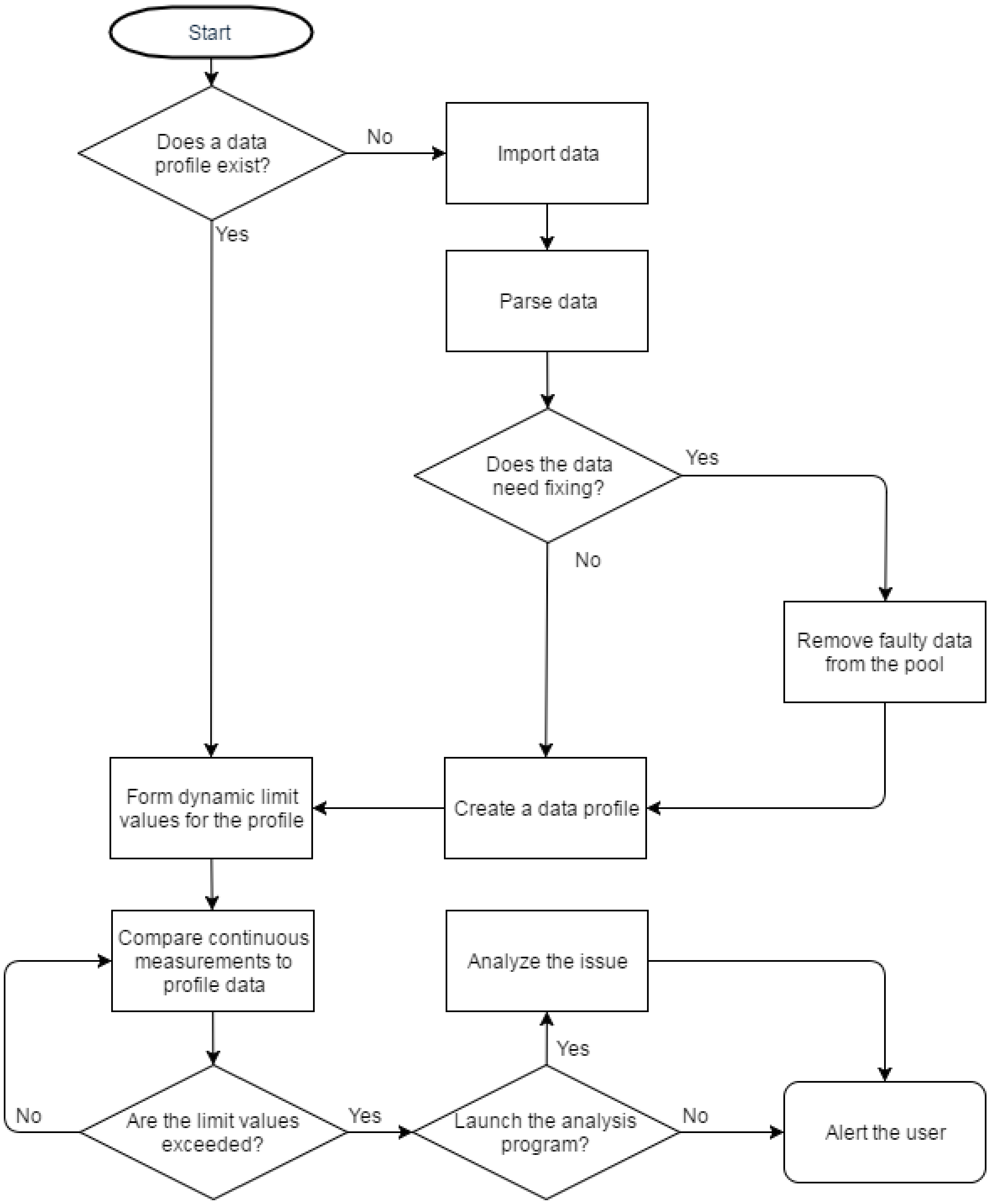


FIGURE 17 Flowchart of the operating principle of the software

The software consists of different functions that are stored separately as .m-files. This is a common practice in MATLAB environment as the functions can call each other, but the user can also call the functions from the MATLAB console. Each file has its own usage instructions commented at the beginning of the file if the user wishes to call these functions separately. This instructions block can be loaded to MATLAB console by typing:

```
help functionname
```

6.1 Importing the data

The data is imported from Savonia Measurements System Sami using .m-file function named Fetcher. It sends a GET-request to Sami to import sensor data from Sami in JSON-format via Sami JSON-interface. Then it parses it and forms a matrix along the parameters specified by the user.

While this function is called by other functions, the user may call it separately from the MATLAB console. The function is programmed to return a numerical matrix according to inputs that can be used for other analysis within the MATLAB environment.

The function can basically be configured to parse any string that has key-numerical value pairs as it has a separate configuration file in which the user can define all the parameters for it to parse strings. It also has options to be fed a string array manually for parsing, and it can fetch strings from pastebin with a set pastebin paste key.

6.2 Creating a profile

A .m-file function named Converter fetches data in hour-sized pieces, converts them in arrays and stores them in .mat-files on the computer. The file structure is "matfiles\sensor\YYYY\MM\DD\(hour).mat". After that an analysis function named Inspector can be used to detect anomalies in the files, and specific hours can be removed from the folders if they contain erroneous data or special cases that aren't wanted in the normal-state representational profile.

A function named Profiler can then be called to construct a data profile from this converted data. It can be assigned to form a 24-hour or a week-long profile of the data and the profile is then saved into file, which structure is "profiles\profile_sensorname" for 24-hour profiles and "profiles\sensor\weekday_sensor" for weekdays. The profile is a 3 x measurements per day -sized matrix which forms from average value on column one, minimum value on column two and maximum value on column three. The profile is saved as a .csv-file and can be read by external programs if wished, however it is designed to be read by the Comparator-function.

6.2.1 Moving average calculation

The program calculates a simple moving average for the data using an evenly weighted user-specified rounding intensity in seconds, e.g. an intensity of 600 would calculate the average to each datum index from the range of ten minutes (from five minutes before the index to five minutes after it). Measurement frequency does not matter as the program handles that by itself. The program checks whether the time range is evenly weighted (equal amount of indexes at both sides plus the current index itself) by using modulo operator to determine whether the number divided by two has a remainder of 1 or 0, and defines weight range by adding the remainder to the intensity and dividing that by two as presented below.

```
weightRange = (mod(rounding, 2) + rounding) / 2;
```

Therefore, the range is always an integer.

The formula for the simple moving average in any point M (in a looping array) with the rounding weight n can be presented as:

$$SMA_M = \frac{x_{M-n} + x_{M-n+1} + \cdots + x_M + x_{M+1} + \cdots + x_{M+n}}{n}$$

And in the sum form:

$$SMA_M = \frac{1}{2n+1} \sum_{i=x_{M-n}}^{x_{M+n}} x_i \qquad (2)$$

6.2.2 Cumulative sum

The program can calculate cumulative sums for data periods (figure 18). The formula to form an accumulative data array suitable for visualization for each datum index M in the can be presented as:

$$AD_M = x_M + x_{M-1} + \cdots + x_{M-M}$$

Where AD_M is the cumulative sum at index M and x represents an index in the array. Cumulative sum simplified in the sum form with the array length n:

$$AD_n = \sum_{i=1}^{n} x_i \qquad (3)$$

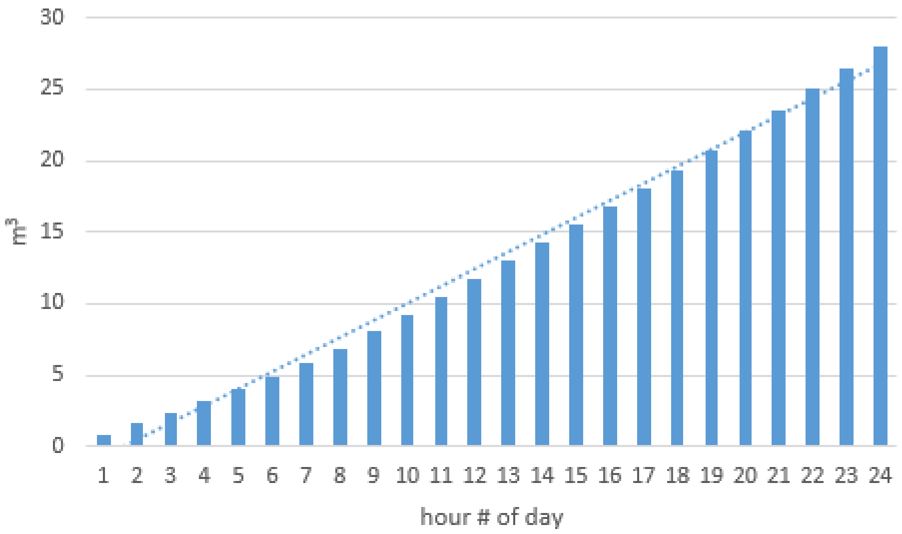


Figure 18 Cumulative sum of a day water consumption

A notable matter in cumulative sums is to know both the measurement frequency and the measured unit. The cumulative sum cannot be generated straight from the continuous data. E.g. if the measurement frequency is once in every three minutes, and the unit is m^3/h the data must first be converted into correct unit by calculating the mean for the one-hour period by following simple MATLAB script:

```
measurementsPerHour = 20;
for i = 1:24
    cumulativeSumArray(i) = mean(dataMatrix(i:i*measurementsPerHour));
end
```

6.3 Defining limit values

A program named Comparator loads up and processes the created data profile to fit user specified parameters such as compression or rounding. Then it forms the limit values for comparison. The limits can set as following:

- Fully user specified
  - The limit is set at specific static value
- User specified conditions based on the data
  - The limit is calculated at each index based on the profile in user-defined calculations, these include values combined by the calculations made from profile mean, set values, and percentage of minimum and maximum values from the data profile
- Dynamic limit values
  - The limit is dynamically calculated from the data pool. The user can specify whether the limit is formed from 24-hour maximum or average deviation from the average profile and whether the limit is implemented as a static value in every profile index or as an added percentage.

6.3.1 Dynamic limit values

The program has options in forming dynamic limit values based on the recorded data. For steady deviation values or applied percentages have been figured to be effective yet simple methods in producing logical dynamic limit values in automated hydraulic monitoring, these features have been implemented in the program's limit value generation.

The formula the program uses for calculating the daily maximum deviation DMD with the day's profile matrix A and recorded day's maximum or minimum value sequence B for that profile:

$$DMD = \max_{j:A_j} \left| B_j - A_j \right| \tag{4}$$

For a more rapidly changing system, like when the system easily fluctuates, and the alert sensitivity is set to relatively low setting, a more careful limit value may be defined. The program has an option for a daily mean signed deviation DMSD, with the day's profile matrix A and recorded day's maximum or minimum value sequence B for that profile the formula can be presented as:

$$DMSD = \frac{1}{n} \sum_{j=1}^{n} \left| B_j - A_j \right| \tag{5}$$

For both of these methods, there are options of taking either the absolute value of the deviation to be added at all index points with the profile value in the limit value sequence, or the percentage calculated from the profile data, which is applied with each index point of the profile matrix and placed into the limit value sequence.

6.4 Comparing values

After the limit value generation and the rounding of the data, Comparator starts to call Fetcher to import real-time data from the database. It presents the data visually by showing the measurements on top of the data profile, and automatically calculates the difference to the generated limit values as seen in Image 5.

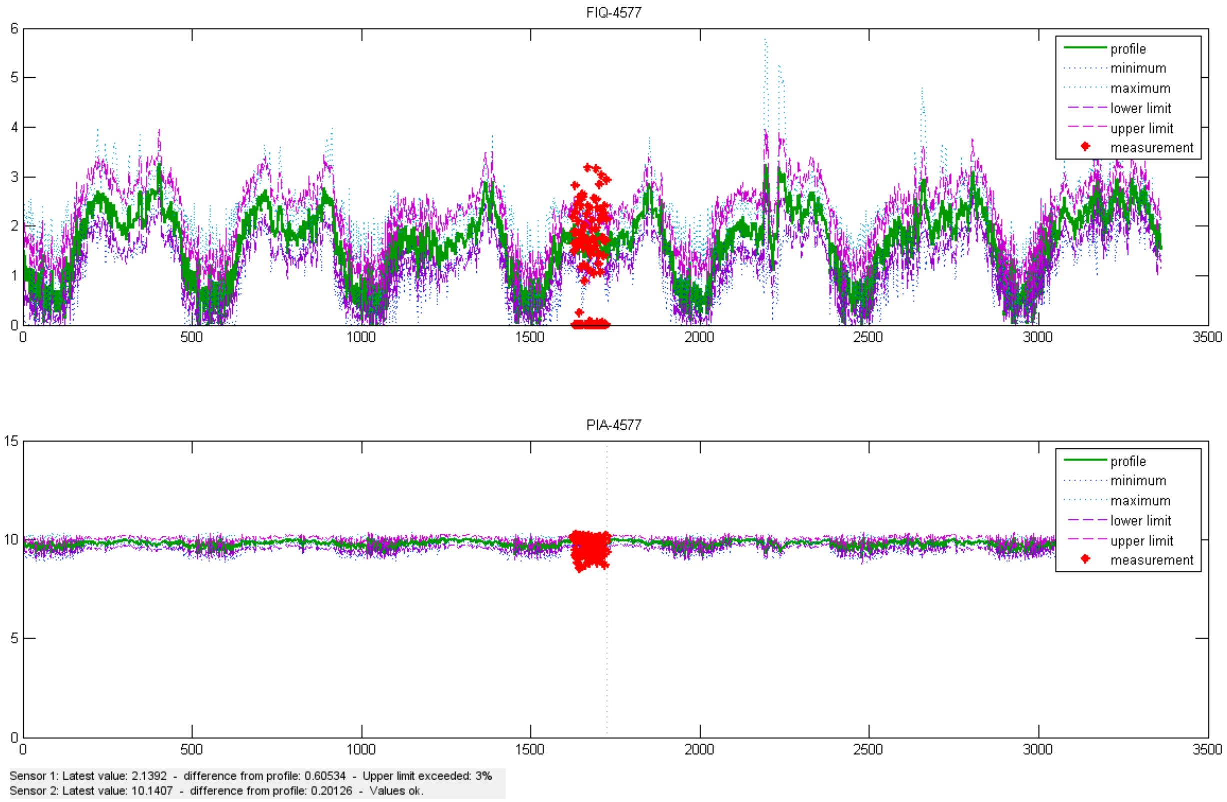


IMAGE 5 Comparator-program recording live data (red dots) and showing it on top of weekly data profiles

6.5 Detecting leaks

Depending on the system, leaks can be detected in many ways. Usually this is calculated by separating a certain section of the pipeline and calculating the difference in water mass between what enters the section and what leaves it, like presented in Function 1. If a notable difference is detected, a leak is a possibility. If the measured values in the program exceed the limit values too many times (specified by the user), the program calls a file "analyse.m". In this file the user can have code for a specific leak detection program suitable for the system. If the function is not available, the program only displays a warning message, like in the logic presented in Figure 17.

7 CONCLUSIONS

The demand for continuous measurement and comprehensive District Metering Areas is in steady rise. Its benefits are becoming more important when water supply networks deteriorate or they are being expanded. Most necessary quantities to measure (at the time of writing) in water supply network DMAs are hydraulic characteristics, i.e. pressure and flow rate. While DMAs are good at reducing non-revenue water and detecting leaks in the network, more advanced monitoring could further improve these systems by making leak detection and localization more precise and faster, combining water quality measurements in the same system and overall automating the monitoring process.

The goal of this thesis was to investigate the needs for a more comprehensive monitoring system in water supply networks, and to plan, design and program monitoring software that can be used in various monitoring tasks concerning DMAs and test systems. The program was written in MATLAB and can be used with real data with the Savonia measurements system Sami or similar data logging software. The hydraulic data from DMAs for research purposes was provided by Savonia Pilot-scale water supply network test system used to simulate a small DMA and Vehmersalmi DMA.

By using this program or implementing its operating principle, the user can Model or form a 24-hour or 7-day cycle data profile to measurement points of the network for any measurable variable based on previous normal-state data of the measurement point. The dynamic limit values, which are being created completely based on the data, are used in determining the current status of the network. Alerts for operators are created by comparing the real-time data with the data profile and its limit values. While the goal was to implement monitoring software for hydraulic characteristics, the way the software is programmed allows the user to profile and monitor virtually any type of numerical measurements or similarly behaving numerical data.

If needed, the program can be further developed by implementing new features to its source code and/or by writing new functions to widen the possibilities in data-analysis. The working principle can be implemented in DMA measuring nodes or in other automated monitoring systems, or the program can be used by itself to monitor nodes by running it on MATLAB.

The challenges in the development process were mostly in the planning of its functionality and to speculate possible methods how to implement the features. There are not similar monitoring programs (as far as the author is aware of) and creating something new is always a challenge in itself. Challenges were resolved best by proceeding step by step in the development process and by focusing on a single task at a time. Researching, speculation and composing of ideas was still a running process along the development.

Important aspects that were learned during the development process:

- It is important to pre-survey data from possible customers to outline the features of the program
- Dividing the possible features into separate groups that can be delved into one at a time
- Writing the program in a way that it is easy to implement possible updates
- Making the program function outputs simple, so they are combinable and callable by other programs as well as from the console by the user (extensibility)
- Comprehensive commenting and documentation for further use of the program is essential

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