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Leak detection in virtual DMA combining machine learning network monitoring and model based analysis

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Abstract: According to international and national standards, the best practice method for monitoring a water supply system is to sectorize it into district metered areas. A district metered area (DMA) is an area with strict hydraulic boundaries within a distribution system with measured inflow into this discrete area. The measured minimum night flow can be compared to a default or to the customer night consumption to calculate water loss. For a supply system with detailed information about the structure, pressure and hydraulic gradients, it is also possible to identify water loss with high reliability using a method of monitoring virtual district metered areas. The presented method was used for upgrading an implemented monitoring strategy for a network in Germany. With this concept the area of a possible leak could be reduced within a virtual DMA to a range of 300m between the prediction and the real leak only by combining the metered flow values and the calibrated hydraulic model.

Keywords: virtual DMA; leak isolation; sensitivity analysis

Introduction

The quality of the infrastructure in Middle Europe has compared to other industrial countries a high level. This high quality is also represented by the study of the world economic forum (Schwab, 2014), where according to the Infrastructure-Index several countries like the Netherlands (4. Rank), Germany (7. Rank) or Spain (9. Rank) are among the best ranked in the list.

Even in highly developed industrial countries with a water supply system in good condition and low water loss, the maintenance of systems and the reduction of water loss are becoming more and more important. But even in those countries the pipe systems have become much older and vulnerable to damage, which will lead to an increase in water loss.

Especially for an efficient management of supply and rehabilitation, the knowledge of failure rate and water loss is important for indication of the systems condition. The application of a GIS, hydraulic network computation software and an adequate Asset Management System is state of the art.

In order to quantify water loss and to determine methods for reducing loss, a reference level or a limit level is necessary. National and international associations (IWA, DVGW) have published performance indicators and reference levels, whose calculation is influenced by several different input factors. The results should support and inform the water supply company about the actual condition of the supply network and make it possible to establish methods for the reduction of water loss.

District metering

The International Water Association proposes to separate the distribution system in district metered areas – DMA. A district metered area is an area with strict hydraulic boundaries within a distribution system with measured inflow in each district. The measured night minimum inflow is compared to the customer's night consumption to calculate water loss (Morrison et. al., 2007).

The advantage of a hydraulically separated area is to measure the system input easily by clearly defined input flow meters. By closing valves the points of inflow are clearly defined. When considering the minimal night flow, the change in inflow will picture the growth of a leakage.

According to the DMA Guidance Notes (Morrison et. al., 2007) a district should have between 500 and 3.000 service connections. When a DMA is too large, changes in flow rate (velocity) measured with an inflow meter can be hardly identified. With an increasing volume of the system inflow, the probability of identifying even smaller leaks with system inflow measurement is decreasing.

When there is a lack of information regarding the hydraulic condition, as well as the flow or pressure situations, a separation into districts with strict boundaries is a simple and efficient method to get an overview of the actual condition. This leads to a possibility to classify water loss by water balance.

The disadvantage of district metered areas is the separation into hydraulically discrete areas with decreasing the flexibility and performance of the system. When a break occurs in an open network, a supply of the customers is normally possible (water can flow through the surrounding pipe sections to the customers). The water supply needed in cases of fire fighting can also be better secured in an open network because the hydrant gets its water from the surrounding pipelines. Creating discrete areas with strict boundaries can result in zones with stagnation, reduced flow velocity and higher retention time with sedimentation or hydraulic problems. Furthermore the implementation of DMA structures usually is cost intensive (installation of additional valves, prevention of dead ends with ring closure…).

Monitoring of an open network with a virtual DMA

The basic methodology of monitoring a virtual DMA is to continuously measure the flow rate at several points and compare the metered data with reference values. In addition to the metered flow data also pressure data can be used. Compared to a DMA these monitored areas have no strict hydraulic boundary. When measuring the minimum night flow, a comparison with former metered data allows the system to identify the occurrence of new leaks. In theory every leak will lead to a specific change in flow or pressure, but the localization of a leak will depend on the accuracy of the water meter.

If the system is not divided into district metered areas the meters have to be positioned at hydraulically relevant points (pipes) over the distribution system to meter significant changes in the flow velocity or pressure. If these significant changes are stable for more than two or three days (nights), this change is highly likely to be based on a leakage and not the influence of customer habits. This change in flow velocity or pressure is measured by the installed meters and is relative to their hydraulic position (closeness) to the leak.

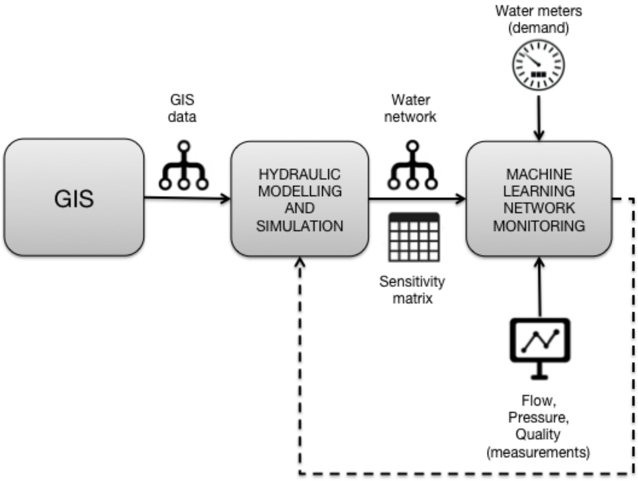

Figure 1 Process chart of software based leak detection

With strategic positioning of flow meters and/or pressure loggers in the network, virtual DMAs are established between these meters. Analysis of the influenced meter spread over the distribution system results in a first rough estimation of the localisation of the leak (Gangl et al. 2012).

Our software-based approach to detect and locate leaks combines machine learning techniques applied to measured data for detecting leak-events, and model-based sensitivity analysis to estimate position and size of the leak (see figure 1).

A model-based sensitivity analysis is used to find the best places where meters have to be installed. This technique is also used to create a sensitivity matrix that helps us to identify the possible location and size of a leak. Different leaks are simulated in every node of the model. As a result we get a sensitivity matrix.

Once meters are installed, the software starts to analyse measurements using machine-learning techniques. This kind of analysis is necessary to filter false positives and to generate warnings only when a real problem exists. If the software detects a problem then the sensitivity matrix is used to fix possible location and size of the leak.

Complex Network - Analysis Management

For a high-grade intermeshed supply structure, the right positioning of a water meter for measuring the flow-velocity is an essential question. In that case, a calibrated hydraulic model of the supply system is a necessary support.

The hydraulic performance of a system can be analysed by using a mathematical model (figure 2). Generally, models should be calibrated by on site measurements (pressure and flow) to eliminate and identify faults such as closed valves, incrustations, and wrong pipe data or pipe connections. A calibrated model is the basis of assessment of pressures and flows in a system and is used for the complete design work.

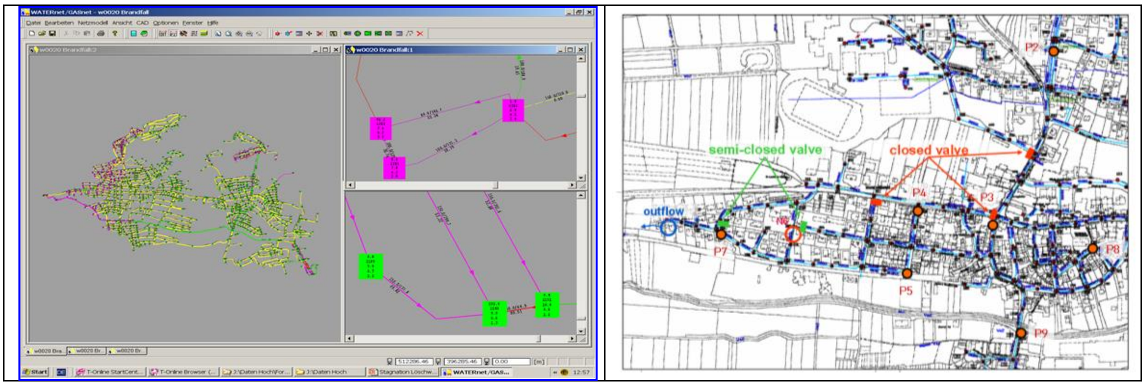

Figure 2 Sample of a mathematical model (Gangl et al, 2012)

Flow Meter Position Optimizer

The idea of optimizing the position of a water meter (e.g. LeakControl) is to visualize the influence of a leakage on the flow condition in the network. With a hydraulic software model it is easy to calculate, which changes in the flow condition will result in the surrounding pipes if a leak of e.g. 1 l/s occur at a specific point in the network. Depending on factors like diameter, material and incrustation, some pipes will have a conspicuous change; others will be uninfluenced of change in flow velocity.

The experience of the author's show, that a flow meter with an accuracy of v = 0.0025 m/s and a low meter barrier of < 1 cm/s can monitor a virtual DMA with 10km length. This area strongly depends on the hydraulic structure and should be seen as a first range.

Figure 3 shows a supply system with a net length of 75 km and a night minimum flow of 60 l/s. It represents the DMA "Niederzone Vaihingen" as one of the 58 pressure zones in the supply system of Stuttgart, Germany and has a high industrial percentage in the southern area. The whole supply zone of 170 km is divided into two parts with three water meters (red dots). The analysis was realized with a leakage rate of 1.4 l/s.

Figure 3 Methodology and result of a simulation with LeakControl Position Optimizer in Stuttgart (Gangl et al, 2012)

The first result of the analysis was that a strict separation of the supply zone with the marked three water meters with a diameter of 600mm is not the best solution for monitoring the system. For a pipe with a diameter of DN 600, the change of the flow velocity caused by a leakage of 1.4 l/s is in that intermeshed structure in the area of 0.004 m/s and close to the low meter barrier of normal water meter.

The red lines in the right hand side of figure 3 show those pipes that are high influenced by the calculated leakage. The results of the computations will lead to a proposal for the optimal hydraulic points for a monitoring system. In that case the monitoring system would exist of 6 sensors (one existing, 5 additional), which represent a meter frequency of 1 sensor per 12 km.

Software based localisation of leaks

A leakage on a pipe will lead to a typical change in the flow velocity in the surrounding area. This characteristic change can be used for locating a leakage based on a hydraulic model.

Normally the annual customer consumption multiplied with factors for different load cases is the basis for a hydraulic analysis. A calibration of the system is executed with a defined outflow and a pressure measurement on several points to identify the pressure reduction in the system. In reality the customer consumption differs more or less between the night and day consumption, therefore differs the theoretical and practical flow situation in the network.

If a meter measures the real system inflow of the water reservoir and the flow velocity during the night times on defined pipes, an ongoing calibration of the hydraulic model is possible (figure 4). On basis of this model, the characteristic flow situation of a leak in the system can be calculated. Hence, the leak shown in figure 4 will lead to a typical change in the flow velocity on the influenced sensors marked with the orange dots.

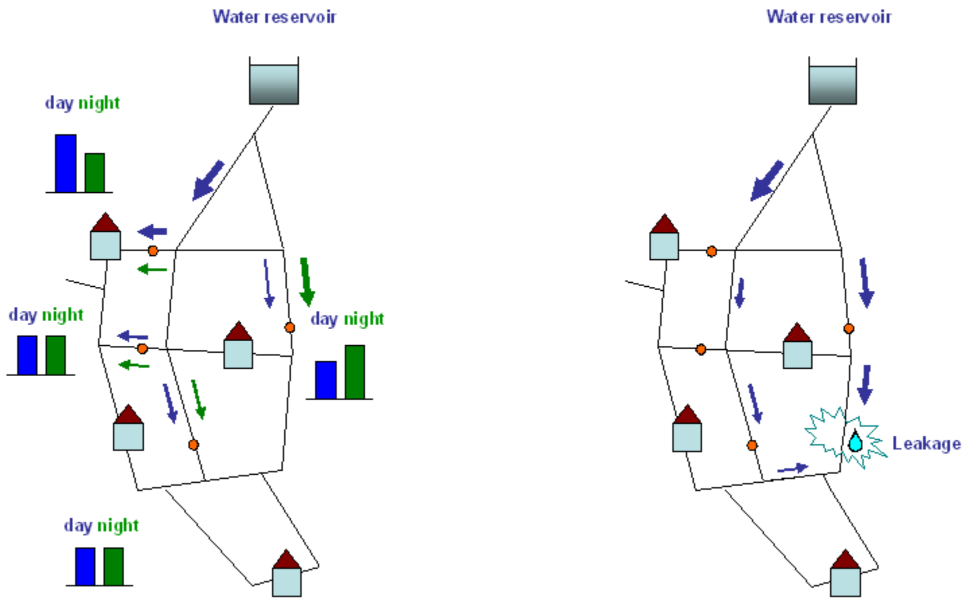

Figure 4 Difference in flow situation between night and day (Gangl et al, 2012)

Case Study

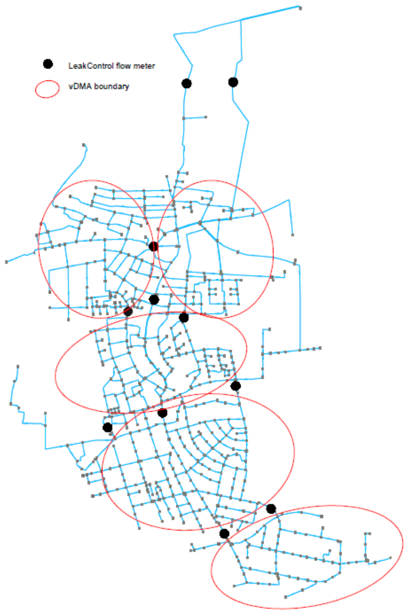

Figure 5 Overview hydraulic model of case study network with vDMA

For a city in Baden-Württemberg, Germany with 44,000 inhabitants, a monitoring concept for the water supply network had to be realized. The system is separated caused by topology into two hydraulic areas. The initial situation was a measurement of the inflow into the two separated areas. With an annual water balance the annual water loss was calculated and depending of the value a leak localisation with noise loggers and correlation was executed.

As this strategy did not fulfil the high requirements of an up-to-date water loss monitoring concept for one of the two parts with a net length of 60km and minimum night consumption of 7.2 l/s an upgrade of the monitoring strategy was elaborated. This upgrade was realized with the implementation of virtual DMA's by using the System LeakControl. The virtual DMA is realised with ultrasonic flow meters with a high accuracy, a low meter barrier and transfer of the measures data via GPRS. The flow data of the virtual DMA can be controlled via a web-based solution. As pictured in figure 5 the red-signed areas represent a virtual DMA structure. By monitoring the flow values of the water meters a rise of values will signalize a possible leak inside of these areas.

As a third step, the actual presented method will reduce the areas of a possible leak inside of the virtual DMA's by using the information of the hydraulic model.

Results and Discussion

With the common monitoring methods an inflow measurement into a defined area (DMA or vDMA) allows a prediction if a leak occurs inside of the monitored area. With a DMA or a virtual DMA a further localization of a possible leak without any information of the hydraulic situation or additional metered parameters inside of the area is difficult.

The presented method uses the metered flow values of fix-installed meters and compares theses values with calculated flow values of the hydraulic model. The best fitted comparison of real and calculated flow values will reduce the area of a possible leak to an area of some 100m. Figure 6 shows the prediction of the leak location. The dimension of the area depends on the complexity of the hydraulic system, the number of installed sensors and the accuracy of the sensors. The actual analysis lead to the result, that with a density of 1 sensor each 10km supply net length and a calibrated hydraulic model an area of a possible leak can be reduced to a region of less than 300m. Figure 7 shows the start of the leak.

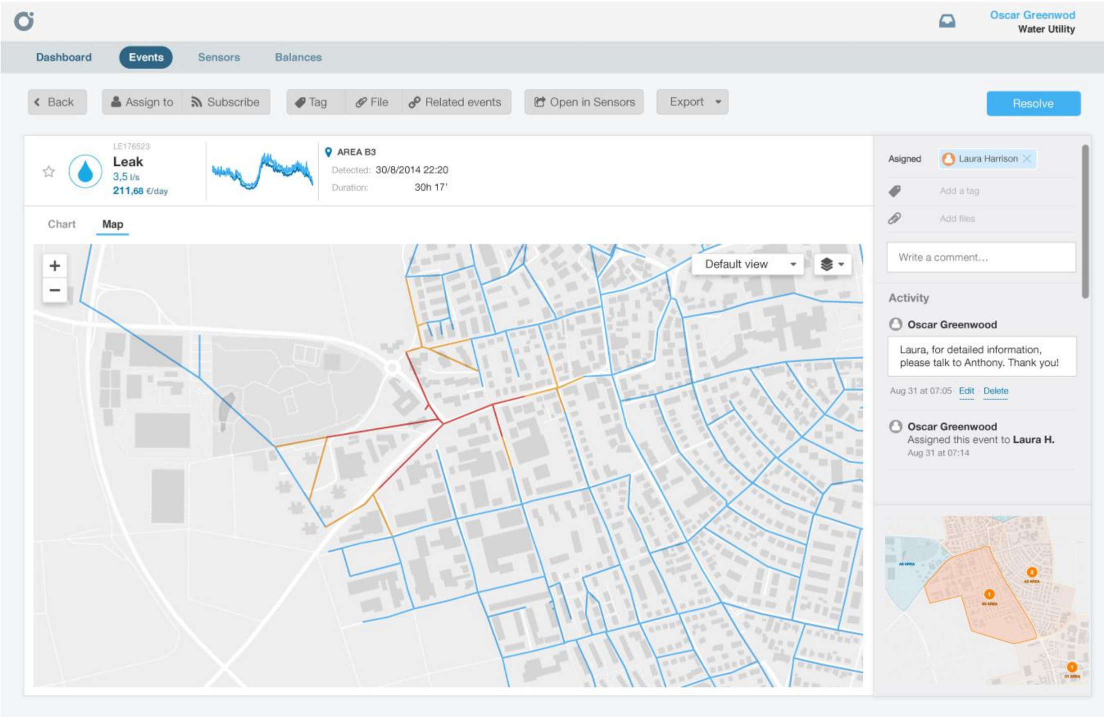

Figure 6 Detail of the location of the leak

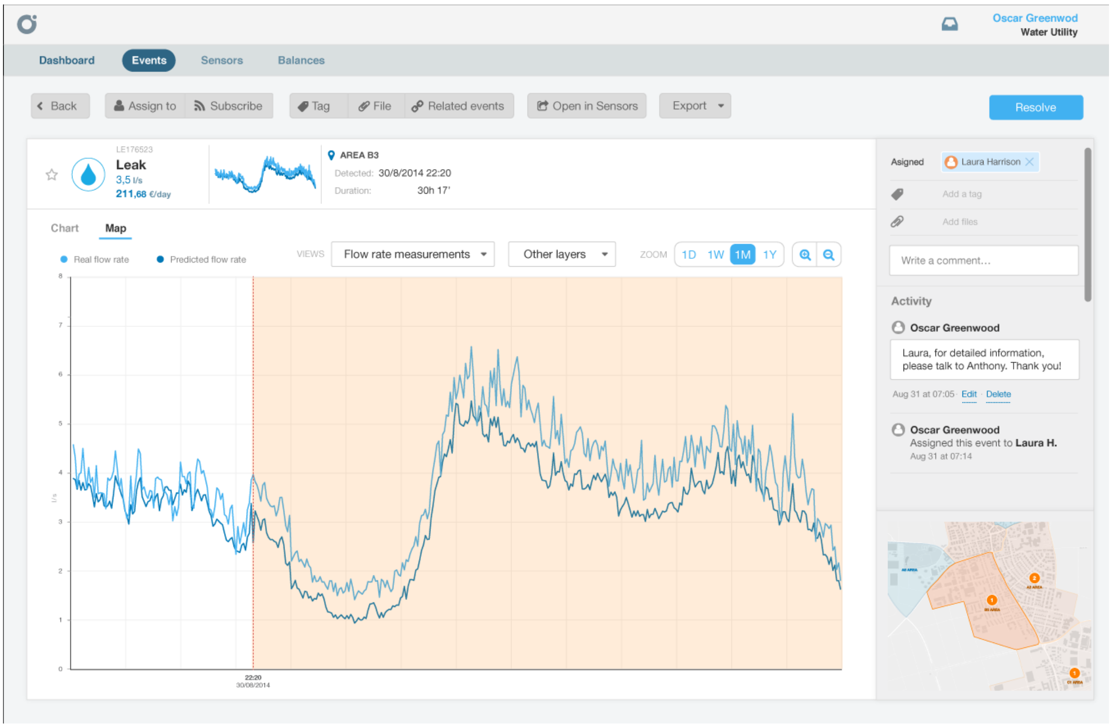

Figure 7 Detail of the start of the leak

Conclusions

For monitoring and measuring water loss in a distribution system, several methodologies are common, which are influenced by material, diameter and other factors. The advantages and disadvantages have to be taken into consideration to find the optimal technique for water loss management in the respective supply system. The strategic methodology presented in the paper is based on a hydraulic model compared with online flow data.

With this idea, on the one hand an online water loss monitoring for an overview of the system's condition is easy to realize. On the other hand a short-term localisation of a leak with the additional information of the volume of lost water is the advantage.

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Risik Management for Water Supply Pipes

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Abstract:

In this paper, the risk of water supply systems as a combination of hydraulic analyses (consequence) and failure probability of pipelines based on the actual condition is discussed. On the one hand a stepwise closing of pipelines calculates the influence on customer's supply which represents the importance of a pipe. On the other hand, based on existing failure statistics, age and material distribution, a failure probability of a pipe segment is calculated. The two factors represent a risk matrix which is crucial for optimising the system.

Keywords: hydraulic analysis; failure probability; risk management; system optimisation

Introduction

According to national standards, water utilities have to guarantee the supply of water to their consumers in appropriate quality, quantity and pressure. Therefore, combining of information about net service, net condition and additional assets is the basis for developing a customized strategic asset management (SAM) and derivate an operative asset management (OAM).

Supply guarantee, supply quality and supply reliability are the cornerstones of a professional asset management. Periodic or condition based inspection, information from monitoring systems and the documentation of occurred failures and the implemented rehabilitation measures form the basis for the development of a state-of-the-art strategy. It is essential to combine the experience of the on-site operational staff and the "theoretically" available data. For a supply system the information of the hydraulic performance implemented in a software based hydraulic model should be state for the art.

Hydraulic Analysis

The actual hydraulic performance of a supply system can be analysed by a hydraulic net-evaluation for several loading cases. A calculation of a defined hydraulic load case (night flow, firefighting,...) calibrated by on-site measurements will lead to significant statements for closed or semi-closed valves, sufficient supply pressure or hygienic problems according to raised hydraulic residence time.

According to the German standard DVGW W 400-1 (2004) a minimum supply pressure of 2.0 bar is required at the customers connection. In case of firefighting a minimum supply pressure of 1.5bar is temporary tolerable.

To set up a hydraulic model with software basic information about the network should be available. Beside a plan of a map including diameter of pipes, installations like valves, booster stations, reservoirs also information about elevation head, customer consumption and special bulk consumer are necessary. Additional information of the existing water resources or information about planned housing should also be taken into consideration.

According to the experience of the author a main step in a hydraulic analysis is the calibration of the network. At a network calibration, pressure loggers a spread over the system and a pressure reduction caused by a defined measured withdrawal are recorded (Figure 1). According to the German standard DVGW GW 303-1 (2006) this pressure reduction should be at least 1.5bar or 20% of the static pressure. For a detailed calibration a factor of 1 pressure per km is necessary.

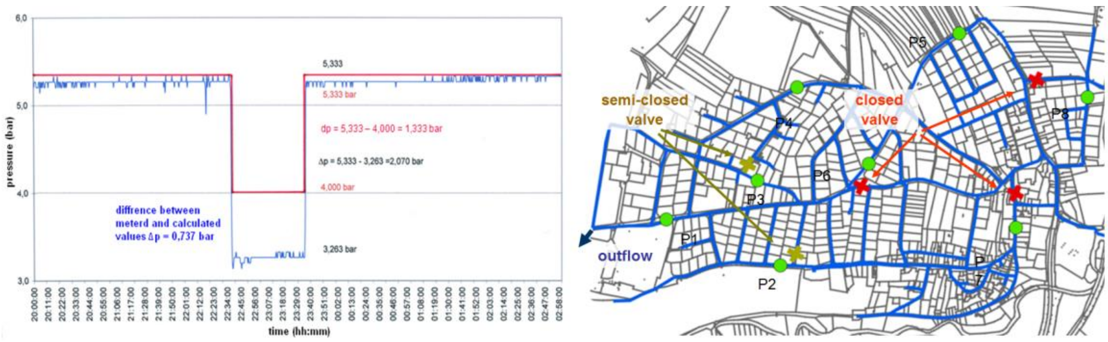

Figure 1 Sample of a result of a network calibration (Gangl et al, 2012)

Figure 1 shows a deviation between the calculated and recorded pressure in a single pressure logger. This deviation might be the consequence of a wrong pipe diameter, a closed or semi-closed valve or a wrong pipe connection. In the last years RBS wave as an engineering company was responsible for more than 60 hydraulic network calibrations of German water supply system per year. There was no supply system which was free of relevant network failures which had an influence of the hydraulic capacity.

In an urban mashed supply network a singular pipe break may have no or less influence on the customers supply, in some cases the pressure will drop marginal. In other cases when the single transport pipe to the network will have a burst the whole are cannot be supplied.

When a calibrated hydraulic model is available the customer consumption will lead to a specific flow of water inside the pipe network. By a theoretical stepwise closing of pipes the influence on customers can be calculated weather the customer is supplied with a pressure below a defined minimum value or is not supplied. According to the percentage of influence of the single pipe with respect to the total supply volume the importance or impact on the system is defined.

Figure 2 shows the result of a relevance-calculation of a supply system with a net length of 130km. As a boundary condition a minimum pressure for customers of 1.0bar was defined. The relevance of pipes is set into relation to values where nodes with customer consumption are below 1.0bar pressure, to nodes below 1.0bar pressure but still with supply and nodes without any supply caused by closing of the pipe.

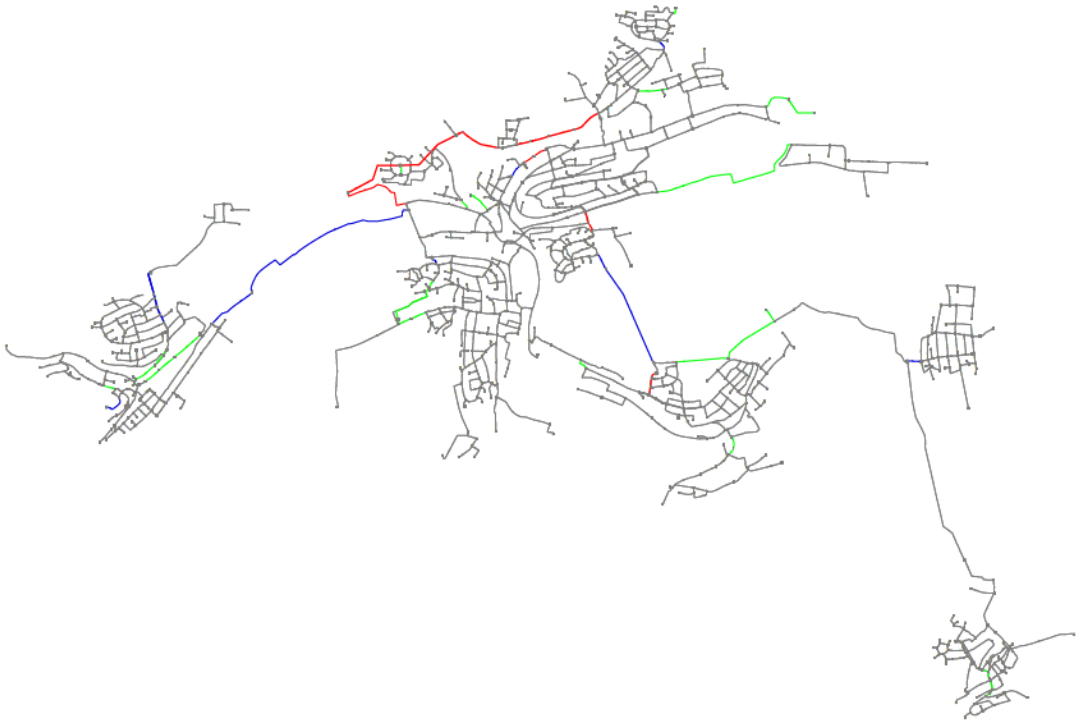

Figure 2 result of a relevance-calculation of a water supply network

The red pipes have a high relevance, followed by the blue and green pipes. For the rest of the network a break of a single pipe has no or only less influence on the pressure at the customers side. For these pipes also a repair-strategy is possible as the customers are not influenced.

Failure Analysis

The ongoing deterioration of the net and the change of the net condition caused by several influencing factors have to be merged and evaluated in a risk management system. An aging function which is influenced by the main factors like year of construction, material, diameter should reflect the utility-specific situation.

To describe this deterioration process, some well-known theoretical probability distribution functions can be fitted to the recorded failure data by statistical analysis (Gangl et al, 2007). Hence, a failure or risk probability for each defined pipe group depending on the ongoing age can be calculated. It is relevant that the utility-specific failure situation will be represented by an aging function. When a standard aging model is used which is not fitted to the actual situation a difference in the rehabilitation need will strain the condition of the network and the necessary investment budget. Figure 3 shows on the left side a fitted aging function to the recorded failure data of a water supply utility for old steel pipes without a sufficient corrosion protection. In the German regulation, for this type of material an aging function is published with obvious longer life time expectancy. The right side of Figure 3 shows the difference of the rehabilitation need by using the literature lifetime expectancy and the fitted aging function. Based on 300€/m for rehabilitation of a pipe the calculation lead to a difference of 7 Mio € for the investment budget!

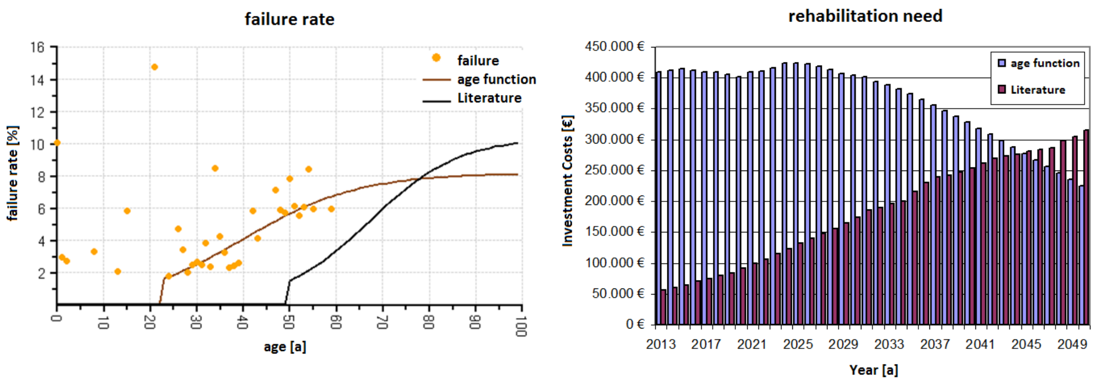

Figure 3 fitted age function to failures and difference in investment need to literature function

A pipe segment will move along the defined aging function from a good condition to a time, where the requirements for a further use are not fulfilled any more. This lifetime expectancy is influenced by several factors. For a utility with high production costs the economic lifetime with respect to the volume of lost water caused by a failure or a leaking pipe connection will be earlier than for a utility with a sand soil, water with a high quality without treatment and no pumping costs. Depending on these influencing factors a water supply utility should set up diverse rehabilitation strategy depending on importance and failure probability (Figure 4).

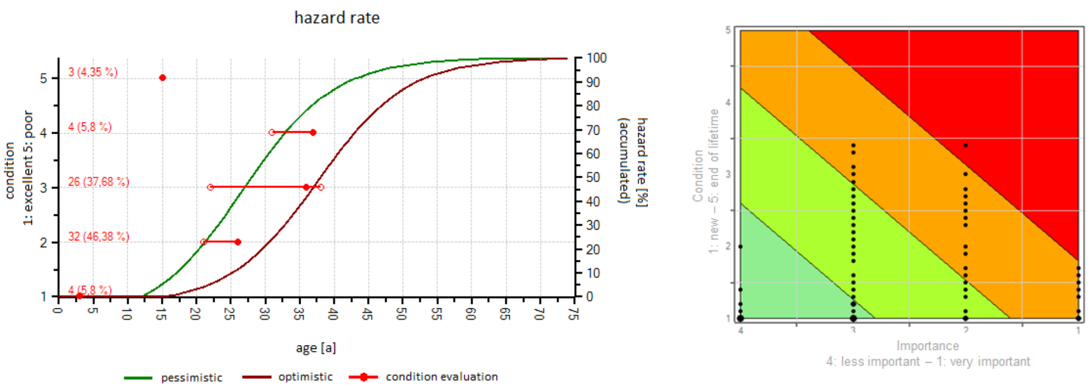

Figure 4 risk matrix based on importance and condition of pipes

Results and Discussion

To set up a risk management for a water supply utility the definition of the considered area and the strict definition of the boundary is relevant. A risk management can have the focus on the resources (contamination of wells or springs...), on the transport pipes and the consequence of a failure of this sensitive infrastructure or the pipe network itself. In the actual paper the risk management is focused on the supply network itself. For large water supply utilities like the water utility of the city of Stuttgart, the responsibilities for resources, transport and storage, and water supply is separated into three departments. It is for sure, that an overall strategy has to take into consideration the results of all three analysed fields.

For a City in Baden-Württemberg, Germany a relevance-calculation and a rehabilitation concept was evaluated. The analyses for the hydraulic calculation of the relevance of a pipe segment were done by the restriction of a minimum pressure of 1.5bar at each node in the network. This is the minimum allowed pressure in case of fire-fighting in Germany; under normal condition a minimum pressure of 2.0bar and additional 0.35bar per every level in a house is required (DVGW W 400-1). For the network also a rehabilitation strategy with fitted aging functions to several pipe groups was elaborated. The database for recorded failure data allowed an optimal fitting of mathematical functions to the available failure data. In that case, the failure probability of each pipe segment as well as the hydraulic relevance of each pipe segment was available.

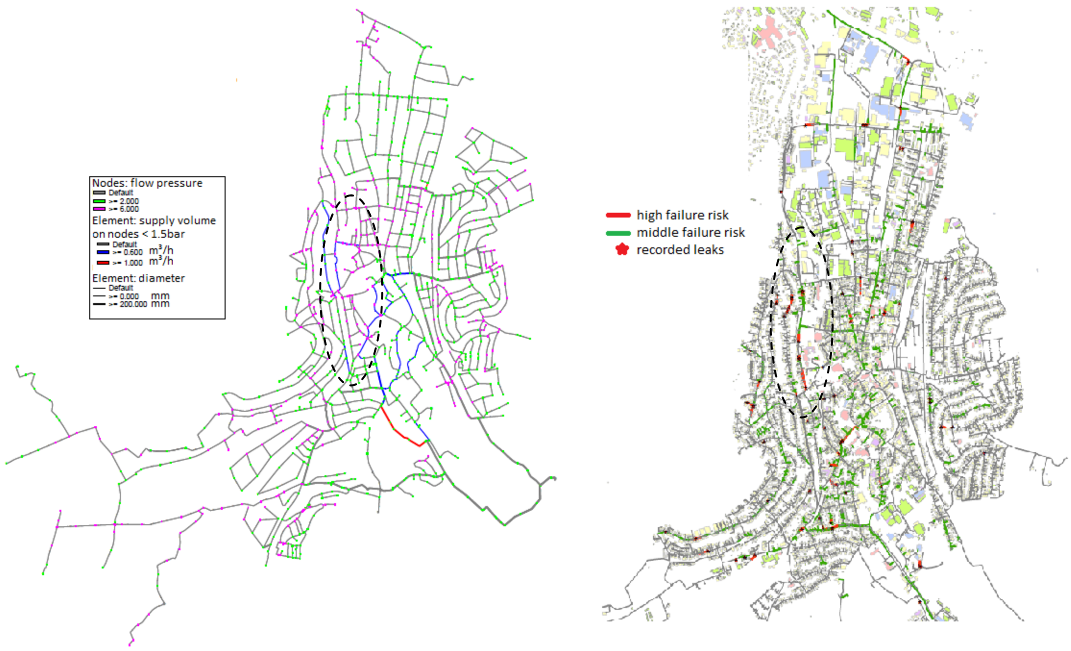

Figure 5 relevance and risk based evaluation of pipe segments

Figure 5 shows the result of the relevance calculation as well as the failure risk calculation of each pipe segment of a water supply network with a length of 174km. In the left picture the red coloured pipes represent pipes which lead to pressure of less than 1.5bar when they are out of order. The volume of water in nodes with less than

1.5bar is more than 1.0m³/h. For the blue pipes the volume of water is more than 0.1m³/h. Under normal condition, the pink coloured nodes have an average flow pressure of more than 4.0bar pressure.

The right side of Figure 5 shows the result of the risk based analysis with respect to an aging model. The red coloured pips segments show a high failure risk. The actual recorded failure data are also marked in the plan.

The black dotted ellipse in both maps represent an area with a high failure risk as well as a high relevance of pipes which will cause a pressure drop below 1.5bar when the pipe segments have to be out of order in case of failure.

Conclusions

The method described is a valid approach to optimise water supply systems based on a risk-management approach. An overall strategy for a rehabilitation of a network should include as well the result of a hydraulic analysis and a failure based analysis. The presented case study of a city in Germany shows the overlapping of pipes with a high failure probability which have also a high relevance for the supply situation in the network. A rehabilitation strategy has to focus especially on those pipes. In a mashed supply structure the influence of a single pipe on the hydraulic situation is difficult to estimate – a software based analysis supports this analysis. The combination of the result of the relevance calculation and a failure probability can result in a better definition of an investment budget and a priority ranking for rehabilitation of pipe segments.

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