



Online water quality monitoring in the distribution network

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Abstract

To ensure the safe supply of drinking water the quality needs to be monitored online in real time. The consequence of inadequate monitoring can result in substantial health risks and economic and reputational damages. Therefore, Vitens, the largest drinking water company of the Netherlands, set a goal to explore and invest in the development of intelligent water supply by implementing a smart water grid. To enable this Vitens has allocated a designated part of their distribution network to be a demonstration network for online water quality monitoring, the Vitens Innovation Playground (VIP). In the VIP a network of 44 Optiqua EventLab sensors have been installed. EventLab utilizes refractive index as a generic parameter for continuous real time monitoring of changes in water quality. The EventLab units in the network transmit their data by GPRS to Optiqua servers where the data is processed using event detection algorithms. Deployed as an online sensor network, it allows early detection and rapid response, as well as accurate location of the spread of a contamination within the distribution network. The use of the EventLab sensor network under operational conditions in the VIP is described and its effectiveness is demonstrated by the detection of two water quality events.

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The research in this paper is presented during the Water Convention at the Singapore International Water Week 2014.

1 Introduction

Safe drinking water is a basic necessity for human health and prosperity. The production of this precious commodity is performed with the greatest care and its quality is strictly regulated and monitored. Water quality, however, is not stable and will change during storage and distribution.¹ Statistics show that 30-60% of water quality incidents are related to events in the water distribution network.^{1,2,3} Such incidents range from water discoloration to accidental contaminations and backflow of untreated water. Additionally, distribution systems are vulnerable to intentional contaminations. The risk of water quality incidents is further compounded by ageing and deteriorating distribution system infrastructures, which result in increased health risks.

Despite the known risks to drinking water distribution networks, quality monitoring during distribution is intermittent and relies heavily on grab sampling. Given the spatial extent of water distribution networks this means that most of the time water quality can only be monitored intermittently and that water quality dynamics within the distribution network remain largely unknown. When water quality incidents occur, consumers are often the first to notice them when they turn on their taps, i.e. at the time when they are about to consume the water, or in the case of pathogens typically one or several days after the water was consumed.^{4,5}

The consumer as first line of detection is an unacceptable yet common situation. Furthermore, the late detection of quality issues hampers identification and isolation of the source (position) and the spread of the contamination, compromising adequate actions. The consequences of inadequate water quality monitoring can be translated into substantial public health risks, economic damages (recovery costs) and reputational damages and liabilities.⁶ An exemplary incident is the contamination of drinking water with treated wastewater in Nokia (Finland) in 2007;⁷ this incident resulted in 8453 cases of gastroenteritis, and costs exceeding 4.6 million Euros for clean-up, reimbursed hospital expenses, claims for damages etc. A recent high profile event, is the contamination of the Elk River (West Virginia, USA) by a spill of MCHM that occurred on January 9th 2014. This spill necessitated interruption of drinking water supply to 300,000 people for 4 days. Recovery of the distribution network was still underway more than a month after the incident, with the smell of MCHM, which has a very low odor threshold, still lingering.⁸ The potential risks and economic consequences make a strong case for continuous monitoring of water quality throughout the distribution network.

In response to the challenges of water distribution network management, smart water networks are being developed.⁹ A smart water network is an integrated set of products, solutions and systems that enable utilities to continuously and remotely monitor and diagnose problems, prioritize and manage maintenance issues and use data to optimize all aspects of the water distribution network. Vitens' objective is to understand its water quality and the condition and performance of its assets at any location and at any moment, use this information to improve the service towards its customers, make its operation more sustainable at a lower cost. Smart water grids enable efficient and reliable water supply by combining and integrating information, knowledge, traditional and new technologies, and creating a base for a more intense customer relationship.

A water quality monitoring solution that covers the entire distribution network needs to meet a number of preconditions, such as robustness and scalability. To keep operational costs at an acceptable level, maintenance and calibration requirements need to be low. In the ideal case a single sensor would cover the entire range of possible contaminants. With traditional sensors and monitors, only partial coverage of this range requires the installation of combinations of instruments.¹⁰ Operating such a suite of sensors is at best feasible at a small number of key locations, but impractical and unaffordable in a distributed network application. Both the capital

costs for a large number of sensor suites plus the required infrastructure, as well as the maintenance and consumable requirements would be prohibitive.

The second crucial component for online and real-time network monitoring is data collection and interpretation. Data collection and transmission to a central database should be fully automated and requires the use of the latest communication technologies to connect to monitoring locations without fixed infrastructure. Data evaluation and event detection should be automated and autonomous, as it is not possible for a human operator to continuously process all the data collected and turn this into information for decision making. Data evaluation at a central level is required, because this allows recognition of spatial patterns in the data as well as cross-validation of results from different locations. Although various software solutions for event detection are on the market, none were designed to manage real-time data collection from a dense network of sensors in the distribution network.

Herein a new approach to water quality monitoring in distribution networks is described, using a generic sensor platform coupled to a web-based data processing and event detection application. The first operational results from a network of these sensors, including the detection of various operational incidents, is presented.

2 Materials and Methods

2.1 Vitens Innovation Playground

Vitens has appointed a dedicated area of its distribution network, the Vitens Innovation Playground (VIP), to the testing of innovative added-value technologies. The VIP is equipped for the testing of newly developed water quality sensors as well as the ICT aspects required for their operation (communication, data transfer, storage, visualization, data algorithms, etc.)

The VIP is located in the north of the Netherlands in the province of Friesland. The VIP area consists of both rural and urban areas and is supplied by three water treatment plants: from the south by the WTP 1 (see Figure 8, production location B) and from the east by the WTPs 2 and 3 (Figure 8, production location A and C). The total number of connections in the 700 km² area is approximately 100,000 and the total length of the mains is 2270 km.¹¹

The distribution network in the VIP can be supplied by either a single water source or water mixed from the three sources supplying the area. This is an important tool that can be used in the understanding of sensor response to different water qualities and to use these responses to model the distribution network. As a reference for newly deployed water quality sensors, the VIP is equipped with sites that accommodate installation of a broad spectrum of sensing equipment.

2.2 Optiqua EventLab

The Optiqua EventLab is a generic optical sensor concept that measures minute refractive index changes in water using the Mach Zehnder Interferometry (MZI) principle.^{12,13} Refractive Index (RI) is a useful generic indicator of water quality as any substance, when dissolved in water, will change the refractive index of the water matrix. The generic Optiqua sensor chip operates at a sensitivity level of 10⁻⁷ in the refractive index, which can be translated to ppm level of most contaminants. This is a sensitivity that allows detection of a many toxic substances at a level where 24h of normal water consumption¹⁴ does not cause an appreciable health risk.¹⁵

In EventLab, the chip is packaged in a probe which is operated in a flow through cell at 100 – 500 mL/min. flow rate, using a pressure regulator and flow meter to establish a constant pressure and flow rate over the sensor surface. The RI measurement is compensated for temperature using the readings of an integrated temperature sensor.¹³ EventLab is equipped with an automatic cleaning system that utilizes a high pressure water jet (distribution mains pressure) to maintain a clean sensing surface.

As part of the project described, 44 Optiqua EventLab sensors were installed in the VIP (Figure 1).

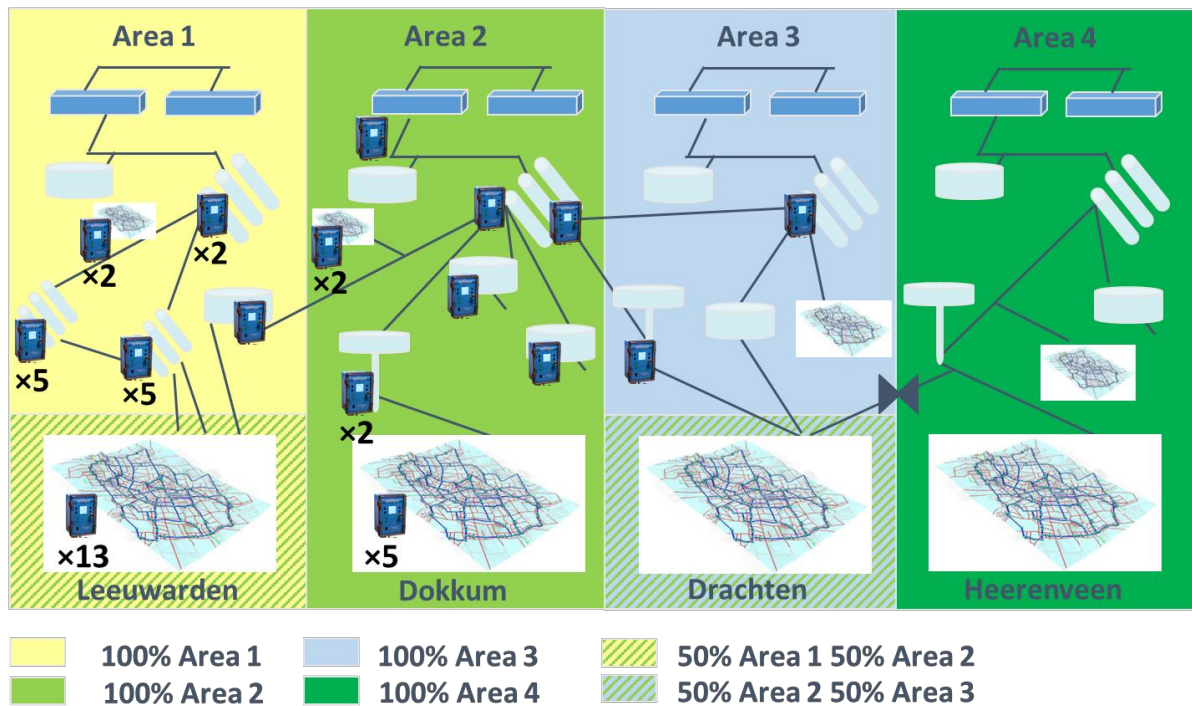


Figure 1: Distribution of the EventLab sensors over the different supply areas in the VIP.

2.3 Data Processing and Event Detection

Next to the EventLab sensors the EventLab systems also consists of a central data storage and analysis software: EventLab Online. The measurement data from the EventLab systems is transmitted to EventLab Online's central data server by GPRS connection. The use of wireless transmission through a commercial cellular network is an advantage for distributed sensor networks, as it requires no specialized communications infrastructure (e.g. SCADA) which would be impossible to implement in many of the (remote) monitoring sites. At Vitens this information is assimilated in an OSIsoft PI software environment for management of real-time data and events which also interfaces with IMQS asset and infrastructure management information software.

Data stored on the central data base is pre-processed before it is used for event signaling. After temperature compensation,¹³ the integrity of the data is verified; outliers are removed, drift is corrected and missing data points are identified and complemented using extrapolation. The verified and compensated data is then processed by the event detection system which detects changes in water composition (Figure 2). Multiple event detection algorithms are used, each one targeting a different type of water quality dynamics (e.g. fast changes vs. slow changes). A combined event signal is subsequently generated by combining the results from the individual algorithms using

conditional rules. The parameters for the conditional rules are defined in a decision table (see Figure 3) and are fine-tuned on the basis of historical data from a monitoring location; each location has its own specific dynamics and the algorithms are adjusted in order to obtain the highest sensitivity at each location. The decision table configuration is dependent on the water utility’s objectives, for example high security requires a lower threshold for Red signals. The fine-tuning of the event detection system for systems installed in the Vitens VIP was performed by Optiqua in cooperation with Vitens.

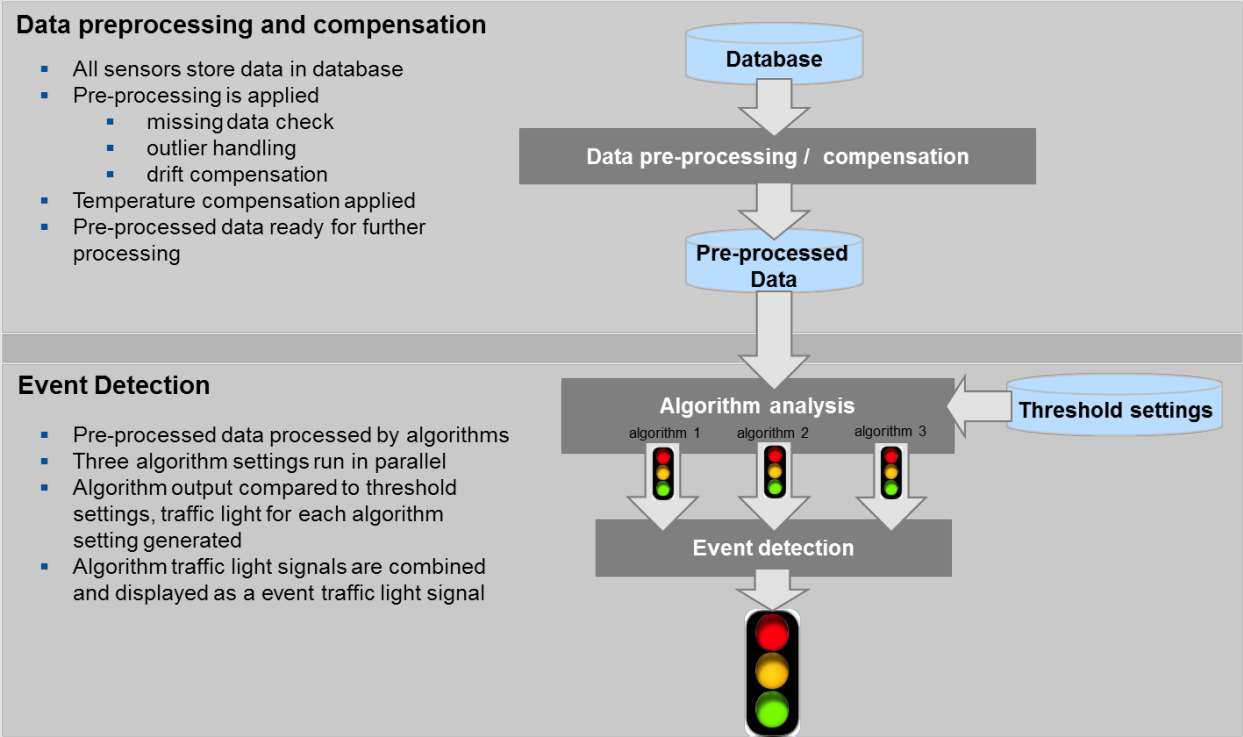


Figure 2: EventLab Online early warning system data processing flow.

algorithm 1										
algorithm 2										
algorithm 3										
Event detection										

Figure 3: Example of combined event signal logic; Green (OK) Orange (Level 1) Red (Level 2).

The basis of the event detection is establishing a baseline setting using historical data. During this training, in which the system learns to handle the natural dynamics of the water quality at particular monitoring locations, the threshold values for the event detection are established. Thresholds can be established based on a long term historical dataset only (fixed thresholds) or by combining this with a short history of data points in a moving time window (dynamic thresholds). In the latter case, the thresholds are continuously re-evaluated and adapted to current baseline dynamics in the data, e.g. due to operational patterns (Figure 4). Subsequently, results for online data from the event detection algorithms are compared to these threshold values and values over threshold are considered events. When the threshold limits are exceeded, water composition has changed beyond the expected natural variation, and an event is signaled. The dynamic approach is best suited for use at locations with large variations in water quality dynamics, as they optimize the event detection sensitivity to match the (in)stability of the water composition due to operational patterns, thus

minimizing false alarms. When using dynamic thresholds the event detection system can provide the highest sensitivity at all times, and highly dynamic water quality resulting from operational patterns will not severely affect sensitivity.

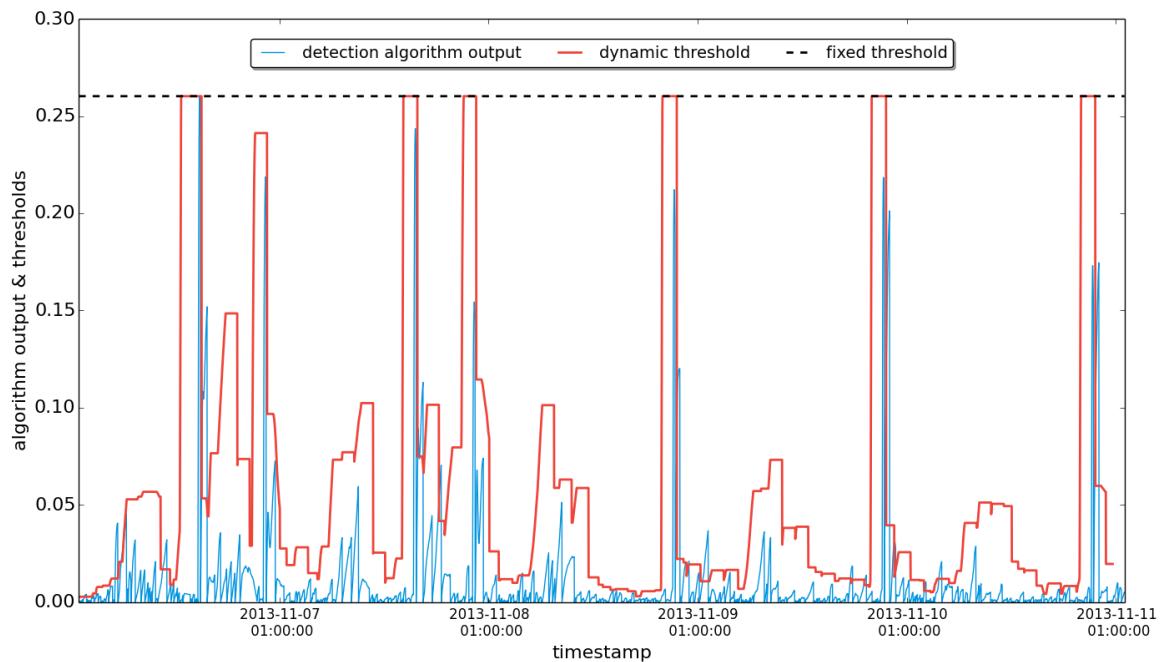


Figure 4: Dynamic thresholding and the improvement in sensitivity over static event detection thresholds.

3 Results and Discussion

3.1 Deployment of the EventLab Sensors in the VIP

A total of 44 EventLab sensors have been installed in the VIP. Locations range from water source (production plant and pumping station), main nodes (water tower, reservoirs, and booster pumps) and further down the distribution network at selected customer locations (e.g. nursing homes, factories, hospitals, residential locations). Customer locations have been selected based on consumption (high and medium volume consumers selected), distance from main distribution lines (as close as possible), and acceptance of customers to participate in development of intelligent water supply.

3-2 Event detection under operational conditions

EventLab and EventLab Online are especially suited to detect changes in water quality. Therefore, Vitens has employed its network of EventLab sensors to detect and track water quality changes in the distribution network. Initial tests under controlled conditions have shown that EventLab exhibits high sensitivity to a broad spectrum of contaminants.¹³ However, a main challenge of operating sensors in the distribution network is to separate the natural and operational water quality variations from the out of the ordinary water quality events. This requires establishing of baseline conditions at the various measurement sites.

Results obtained at the various types of monitoring sites show a marked difference in background variability of the measurement signal. Systems installed at treatment plants and pump stations

typically show gradual changes representing slow changes in water composition, which can result from changing process conditions and from (daily) supply and demand variations (Figure 5). For example, in reservoirs and water towers it was possible to determine the difference between filling and emptying of the system. High frequency and erratic quality variations are more common when EventLab systems are installed towards the consumer as their consumption and flow patterns are dominated by single activities (washing machine, toilet flushing). However, also larger customers, such as industries, can show erratic baseline signals. Dealing with this type of variability is therefore crucial for a successful implementation of robust yet sensitive event detection throughout distribution network

In order to deal with such highly dynamic behavior, it is essential to use dynamic event detection thresholds. With fixed thresholds only, the necessity to prevent false alarms during the variable periods would render the system insensitive to relevant water quality changes.

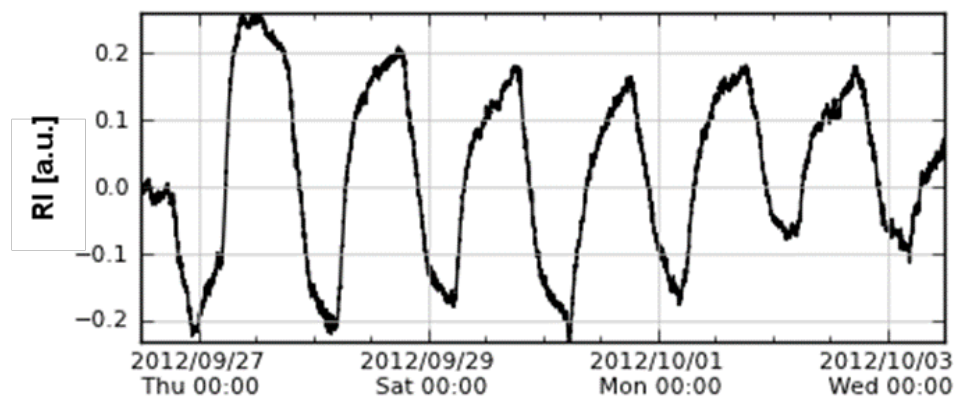


Figure 5a: Distinct but regular daily pattern in RI due to gradual water quality variations at a pump station.

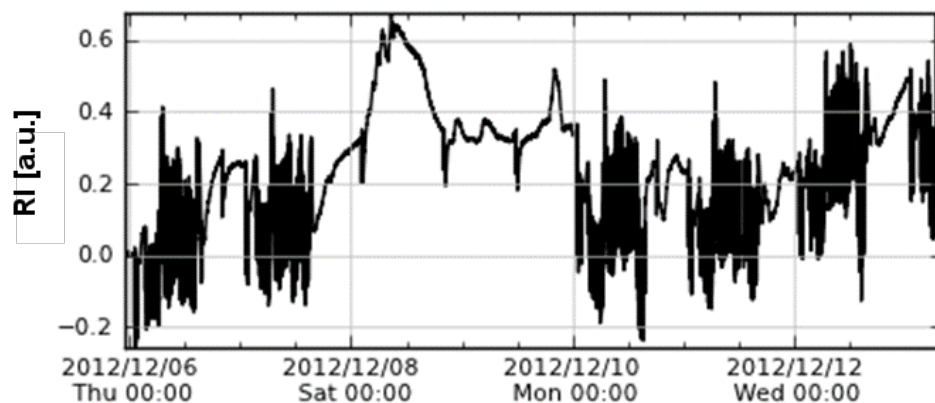


Figure 5b: Highly irregular measurement result during daytime at a meat processing factory, with low variance at night and during weekends.

The benefits of using dynamic thresholding at locations impacted by operational usage patterns was evaluated using artificial spiking experiments; a simulated “spike” is superimposed on event free baseline data.¹¹ Artificial spiking experiments were conducted with azinphos-methyl, urea,

acetylsalicylic acid and potassium chloride. The “spike” is shifted in time to cover the entire time-base of the event free baseline data and the event detection algorithm is used to analyze the spiked data set. The amplitude of spike is increased until the point that 100% of the spikes are detected by the algorithm. The corresponding concentrations for the four “spiked” compounds are then established based on result from earlier dose-response measurements.¹⁵ Detection of a spike means that the combined detection algorithm output exceeds the threshold levels and triggers the combined event signal. Figure 6 presents the improvements possible when applying dynamic thresholds, in this case an average improvement of 2 to 3 time is achieved over the period analyzed and a factor 26 for around 18% of the period analyzed.

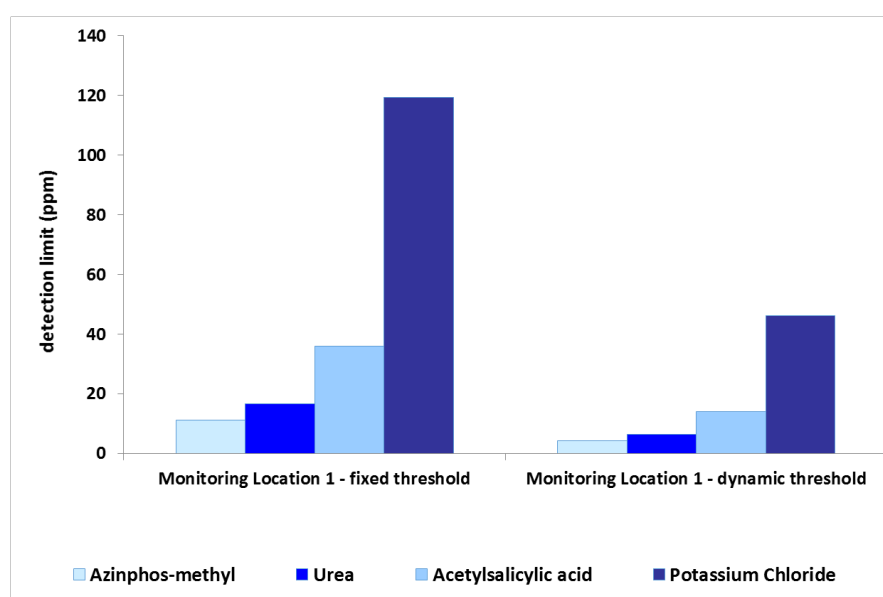


Figure 6: Dynamic thresholding improves average system sensitivity outside of operational usage patterns.

3-3 Detection of a major pipe burst

A further event detected by EventLab occurred in March 2013; a major pipe burst that left the entire city of Leeuwarden without water for several hours. Repair crews needed 2 hours to find and isolate the leak, after searching throughout the entire city. EventLab detected the pipe burst, and provided a general indication of the site of the leak using the sequence in which the individual sensors responded (Figure 7). With EventLab’s information the search area could have been narrowed down and the time to find the leak could have been reduced to significantly less than 2 hours.

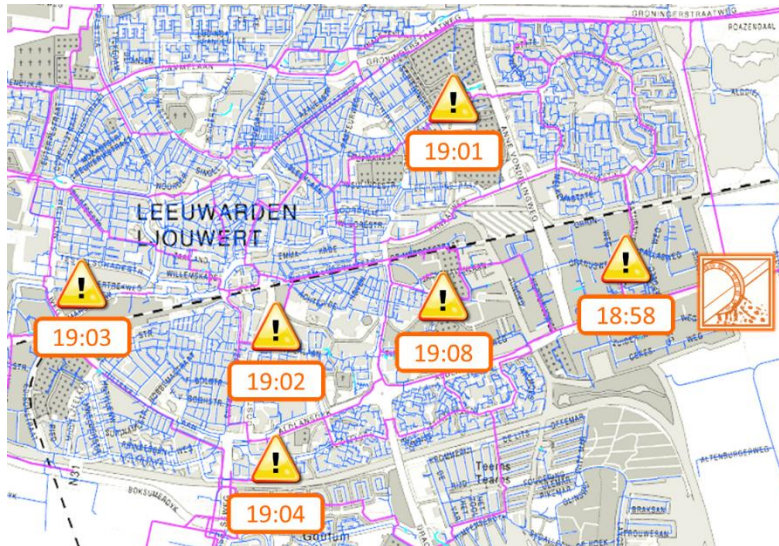


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Figure 7: Time of response of EventLab systems in Leeuwarden to major pipe burst.

3-4 Detection of water quality event due to WTP maintenance

On the 4th of October 2013 Vitens performed planned maintenance at one of their treatment plants (Plant A in Figure 8). The plant in question supplies Area 2, including the city of Dokkum, as well as a part of Area 1, including the city of Leeuwarden (Figure 1). The maintenance necessitated the shutdown of the production at the plant and a temporary reliance on storage reservoirs to keep up the water supply in Areas 1 and 2. Also, supply to the city of Leeuwarden was stopped, with the Leeuwarden supply taken over fully by plant B in Area 1. Although production was planned to be offline for several hours, recurring software issues forced postponement of the restart of the water production resulting in disrupted water production for the following 36 hours. In order to keep up the supply, input from a secondary plant (Plant C in Area 3) was increased. Furthermore, production was restarted temporarily during night hours to top up the reservoirs. During these restarts, the process was run under manual control, and on the second day the treatment was operated without softening. As the hardness exceeded consent limits, notification of critical customers, including health care centers and dialysis patients, became necessary.

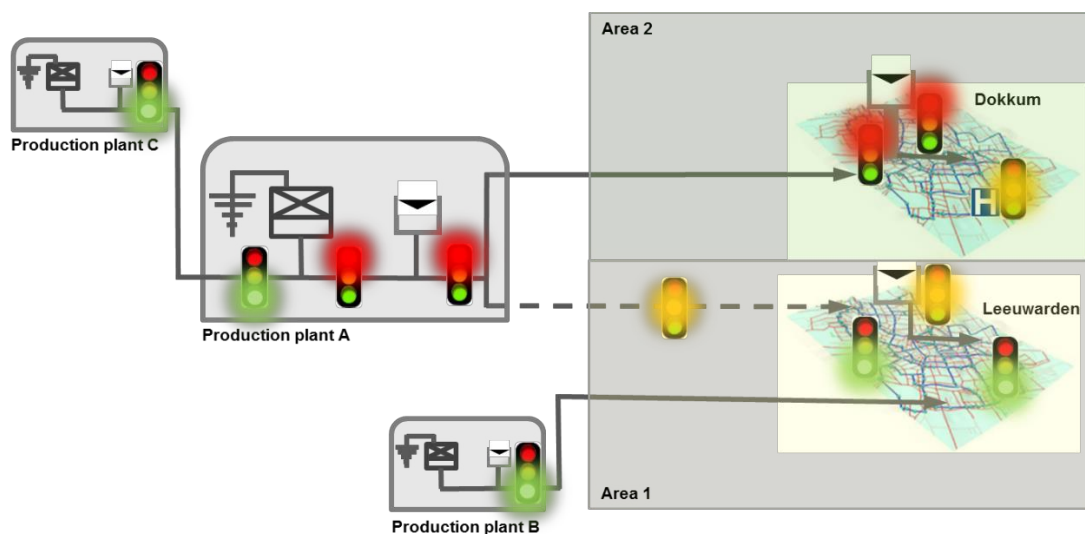


Figure 8: EventLab systems installed in affected area monitor spread of water quality fluctuations through the network.

During the initial hours of the 4th of October, as the network was being fed from reservoirs, no change in water quality was visible. However, as production was restarted to top up the reservoirs and increased flow of water from the auxiliary plant was added to the mixture, clear changes in water quality became visible. This can be explained by the fact that while the plant is running under manual control, different set points are used compared to routine operation, resulting in a different treated water composition. Furthermore, the composition of the water delivered from Plant C is significantly different from the water produced by Plant A¹⁶ thus changing the mixing ratios of water from these plants will also result in water quality changes downstream from Plant A in the supply areas 1 and 2. The production of water with no softening on the 5th of October then introduces a further water quality change. All these variations in composition are clearly reflected in the RI measured by the EventLab systems installed in the area of the distribution network affected. Other sensors installed at the treatment plant, including pH and turbidity sensors, did not detect the changes in water quality (Figure 9), further demonstrating the strength of EventLab's generic sensor concept.

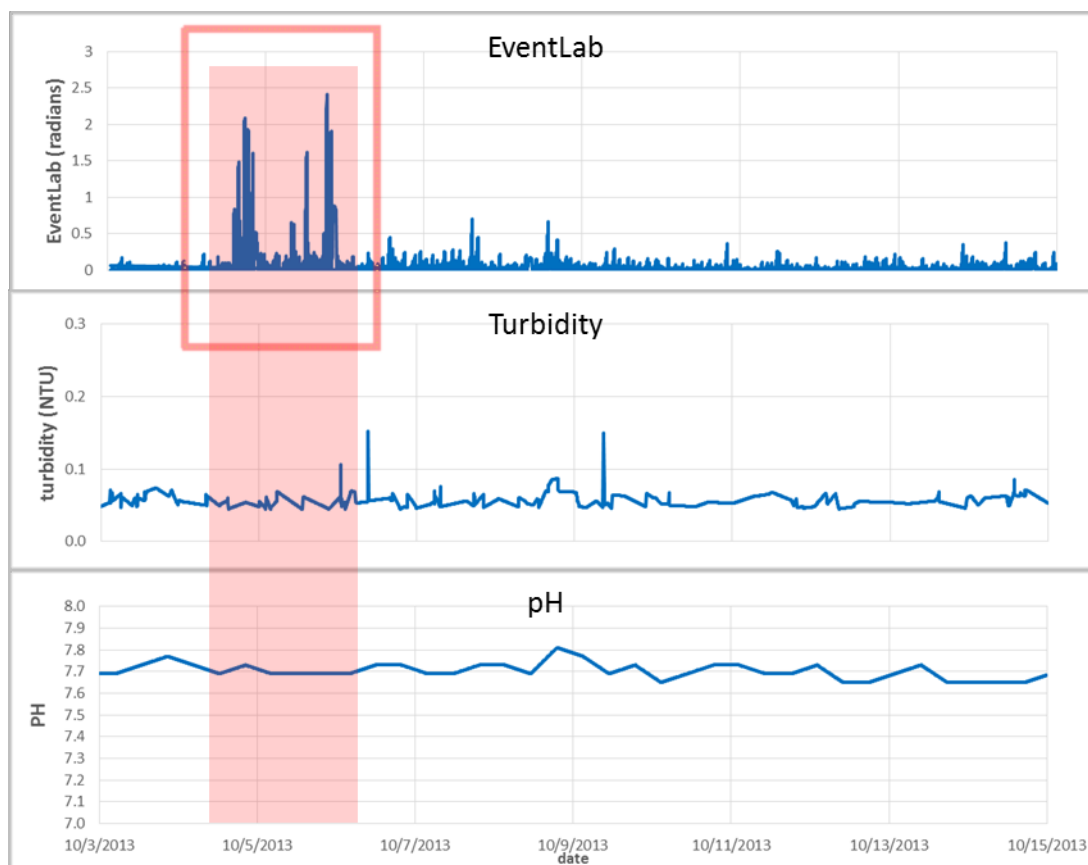


Figure 9: Only EventLab detects WQ event (duration of operational issues indicated in red).

EventLab Online detected the maintenance induced water quality variations, which triggered event signals of the highest status (high probability of an event) at the EventLab sensors installed at Plant A. Furthermore, EventLab sensors installed in supply area 2, i.e. the area supplied by Plant A, also detected the abnormal water quality change. The intensity of the events decreased (level orange, possible event) with increasing distance from Plant A. This can be explained by dispersion and diffusion effects in the network.¹⁷ Similar water quality changes (orange level) were also detected in supply area 1 after the supply from Plant A to this supply zone was re-established.

The transport of the affected water through the distribution network could be tracked by the times at which the individual sensors reported water quality events; the residence time of the water in the network matches the delay in response between the sensors (Figure 10). The information provided by EventLab on the hydraulic residence time of the water in the network during the changeable flow conditions resulting from the operational changes provided Vitens with input for fine-tuning of its hydraulic network model.

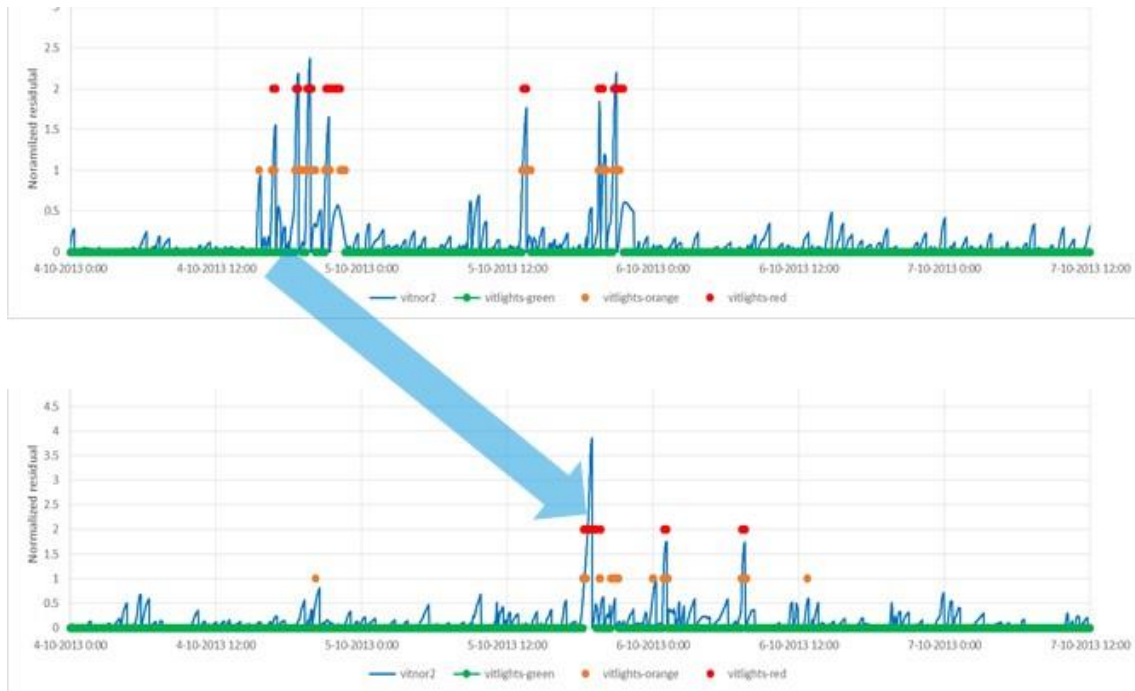


Figure 10: Top; event signals at Plant A due to water quality variations resulting during event on October 4-5. Bottom: Event signals at Water Tower Dokkum due to same event. The delay in response time corresponds to the hydraulic retention time in the network as predicted by Vitens hydraulic model.

4 Conclusions and Outlook

A grid of EventLab sensors has successfully been deployed in the VIP. Locations for installation range from the source, main nodes, and high-volume consumers up to residential consumers. With EventLab Vitens has realized a monitoring network that is capable of detecting water quality anomalies in its distribution network. Where in the past water quality issues in the network were nearly impossible to detect and trace, it now has the capability to follow such events in real time.

EventLab's ability to detect abnormal variations in water composition due to operational events has been successfully demonstrated. Monitoring the issues resulting from plant maintenance, something conventional sensors were unable to pick up, are a first example of what this network is capable of. A second demonstration of its detection capabilities was the real-time detection of a major pipe burst in the Leeuwarden supply zone.

From the evaluation process we have seen that the EventLab early warning system is able to detect water quality changes that relate to contamination levels that are of relevance to the drinking water industry. A dynamic thresholding methodology has been developed, which maximizes the sensitivity of the EventLab Online event detection system at installation sites with highly variable water quality

due to operational activities, e.g. sites with strongly fluctuating usage patterns and or source switching.

As a next step, Vitens will focus on the further integration of the EventLab network into its organisation, taking it out of the realm of innovation and into an operational asset. Critical (re)evaluation of sensor placement, network density and critical assets that require monitoring, as well as developing plans for the deployment EventLab outside of the VIP. Furthermore, response protocols and action plans to act on the information collected by the water quality monitoring network are to be developed. When these are in place it will be possible to achieve the full potential benefits, such as reducing complaints of water quality incidents by pro-active informing customers, improving operational control of the water supply as well as optimisation of network maintenance and repairs.

This work will be performed as part of the recently commissioned European Community 7th Framework Programme project SmartWater4Europe.¹⁸ As part of this project, Optiqua will also implement and demonstrate EventLab systems at a number additional European water utilities.

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