World's Largest On-line Real-time Water Quality Monitoring Network in a Drinking Water Distribution Network

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Abstract
There is a general consensus in the water industry: to ensure safe drinking water supply in the future real-time online water quality monitoring is the solution. But this is more challenging than one would expect. To take on this challenge Vitens allocated a designated part of their distribution network to be a demonstration network for online water quality monitoring, the Vitens Innovation Playground (VIP). As a next step Vitens started two new projects. The first (Meeting of Water) is a large scale physical model of the VIP, experiments not possible in real-life can be performed in this system. The second project, Friesland Live (FL), will focus on operational implementation of the successes of the VIP program. This paper presents recent achievements and challenges in FL, 1) implementing and maintaining a smart water grid 2) evaluation of sensor data 3) defining and implementing response strategies using online water quality sensors. This information can be used by other drinking water companies to form their own business case.

Keywords
Water Quality Sensors, Sensor Networks, Sensor Placement, Vitens, Smartwater4Europe, Water, Quality, Response Strategy, Demonstration, Smart Water Grid, Intelligent, Supply, Distribution

INTRODUCTION

Currently grab samples are taken and monitored in the laboratory; this takes a lot of time and effort. Drinking water companies run the risk to miss an event, this is due to the limitations of grab sampling (transportation time and the time it takes to analyse the drinking water sample) and getting a representative sample at the right time (Thienen *et al* 2016). Inadequate monitoring can result in substantial health risks and economic and reputational damages.

To solve this problem, Vitens, the largest drinking water company of the Netherlands, is investing in intelligent water supply by implementing a smart water grid. In the past years Vitens designated a part of its distribution network as a demonstration network for new technologies, such as online water quality monitoring solutions. This is the Vitens Innovation Playground (VIP) (de Graaf *et al* 2012, Williamson *et al* 2014). The program and results from project out of the VIP have been a success and as a next step towards a company-wide smart grid solution Vitens has started two new projects. The first (Meeting of Water) is a large scale physical model of the VIP, making it possible to perform experiments not possible in real-life (IJszenga *et al* Unpublished). The second project is Friesland Live (FL) which will focus on operational implementation of the successes of the VIP program.

Vitens its goal for this VIP program is to 1) become more energy sufficient 2) faster and more accurately detect and locate leaks 3) implement online water quality monitoring of the distribution network, and 4) define appropriate response strategies (de Graaf *et al* 2012, Williamson *et al* 2014). This paper describes recent achievements and challenges concerning the transition from the VIP program to the FL program. Here we describe 1) implementing and maintaining a smart water grid 2) evaluation of sensor data 3) defining and implementing alternative means of communication and response strategies. Thus we provide novel insights for other utilities implementing smart water grids.

FRIESLAND LIVE

Starting 2016 Vitens decided to implement Friesland Live (FL). FL comprises the whole province of Friesland (over 5.500 km^2) and a distribution network of 8200km with 300.000 connections. In FL over 200 water quality sensors from several manufacturers were installed in addition to 50 District Metered Area's (DMA). Data from all sensors is collected in the Vitens data center via Pi (Osisoft) (Figure 1), processed and presented on a user interface (Figure 2). Based on the integrated data the best response is determined.

IMPLEMENTING AND MAINTENANCE

Sensor placement

One of the challenges with using water quality sensors is to find a good location to place the sensor (Thienen *et al* 2014, Thienen *et al* 2016). We have performed a placement strategy based on several criteria but observed that the sensor placement models are in practice not always useable. The theoretical and practical performance of the sensor network was compared, evaluated and validated, resulting in further optimization of the sensor placement model (Thienen *et al* 2014, Thienen *et al* 2016).

Data transfer

In Figure 1 a schematic is displayed of our current data network. In our District Metered Areas (DMAs) we measure flow, pressure, temperature and conductivity. These data are logged and transferred to our DataWatt server in the Vitens data center. Data from DataWatt is pushed to Pi, where algorithms or other data handling can be performed. Data in Pi is displayed on the control room dash board. Currently for Optiqua Eventlab we have the data from the sensors go the Optiqua server, where the data is processed and validated, and this data is pulled via an XML interface into our Pi servers. Data from the Optiqua Eventlab sensors is displayed on our control room dash board (Figure 2).

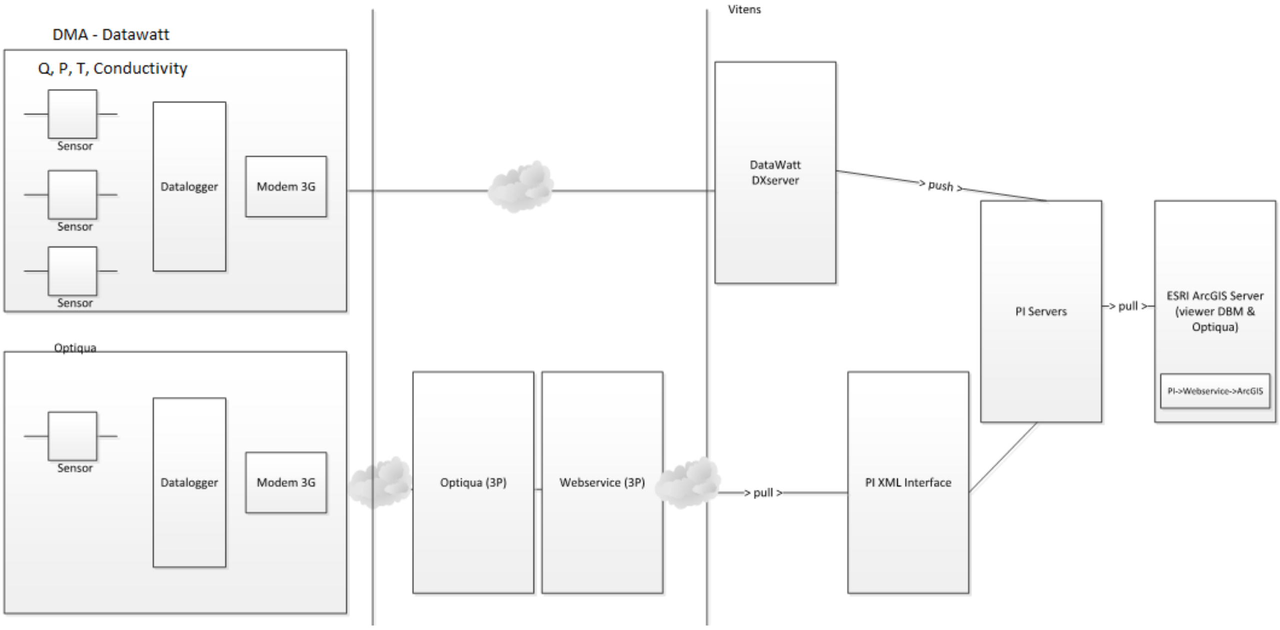

Figure 1. Schematic of data transfer

Data handling

In addition 2015 was used to measure the amount of data we expect to produce in FL. We did this by extrapolating the data from 2015 to FL. As we anticipated it is not the storage of data that is going to be challenging, rather the vast amount of data points that are collected. Handling these data points and moving from data to information is the next big challenge.

Table 1. During 2015 we registered the data points collected and total storage and extrapolated this to FL. The results of this extrapolation a listed in the table.

Data	Data points (Million/year)	Data Size (Gb/year)
DMA (150 measuring stations)	575	14
Optiqua Eventlab (80 sensors)	340	8
Other water quality sensors (120 sensors)	250	6

Sensor maintenance

Another challenge implementing a vast amount of (water quality) sensors is the maintenance. Vitens has evaluated well over a year of the Optiqua Eventlab sensor maintenance and used this information to form a business case. We now have the figures that demonstrate the amount and type of maintenance, and give insight in the skillset of personnel needed to keep the network operational. In 2013-2014 45 Optiqua Eventlab sensors were installed (de Graaf *et al* 2012, Williamson *et al* 2014), therefore the data in Table 2 is based on 45 sensors. For 2016 and further we are also keeping a log of the sensor maintenance of the sensors in FL.

It needs to be emphasized that most sensors were installed in 2013-2014, so the time spent on instalment is not included in these numbers. Depending on the distance and location on average we are able to install 4 sensors per day. The sensor placement and time spent listed in Table 2 is the time it took to move 18 (out of the 45) sensors to a new location based on the study of Thienen *et al* 2016. With an efficient planning and easy access to a sensor location we can clean up to 6-8 sensors per day.

Table 2. During 2015 we registered the hours our maintenance engineer needed to keep the sensor network in the air

Overview Sensor Maintenance 2015	Time (Hours)
Sensor maintenance*	250
Sensor Placement	70
Total travel time (20 trips)	40
Average time per sensor (45)	8

*This includes cleaning of tubes, flow cells, chip surface and data communication.

EVALUATION

Events detected by Optiqua Eventlab

During 2015 we have logged all the Optiqua Eventlab sensor signals. In Table 3 an overview is generated of all the unexpected water quality changes.

Table 3. Unexpected water quality changes that were measured with the Optiqua Eventlab sensors in 2015. Noticeable is that further down the distribution (closer to the customer) events decrease.

Overview Events Optiqua Eventlab 2015	Number (N)
Unexpected water quality changes measured at three treatment plants	147
Unexpected water quality changes measured at 7 booster pumps	93
Unexpected water quality changes measured at 6 reservoirs	117
Unexpected water quality changes measured at 24 sensors placed at customers	34
Number of times multiple (>3) sensors responded after one another	5

Although we detected a lot of changes in the water quality at single sensor location, we had a hard time explaining a lot of these events. This was due to several new insights:

1) When an event occurs you need to 'research' immediately what is going on i.e. when you wait several hours, a day or longer information gets lost; registration of changes in processes and maintenance logs need to be more detailed and improved.
2) Eventlab measures changes in the refractive index; the advantage is that is (very) sensitive (Tangena *et al*, 2010, Wijlen *et al* 2011, de Graaf *et al* 2012, Williamson *et al* 2014), the disadvantage is that its generic; further combining other sensor data (for example with turbidity and conductivity) and other information is necessary.
3) We learned that we further need to optimize our hydraulic models and improve valve registration (i.e. open vs. closed).
4) We discovered that the 5 'major' events were all operational i.e. unexpectedly the hardness changed drastically, or a pipe burst occurred on a larger pipe.

Event classification

In order to come to more detailed information about the events that might be occurring we performed spiking experiments on a small-scale model of the Vitens Innovation Playground, called the Meeting of Waters (IJszenga *et al*, Unpublished).

After spiking close to one hundred components on different concentration levels and by using Principle component analysis (PCA) (IJszenga *et al*, Unpublished) on sensor data (Refractive Index, TOC and Conductivity) we came to the conclusion that we can classify events into groups. By using these data we are able to differentiate between: 1) Organic and inorganics 2) Contamination of surface and groundwater 3) Changes in Metals at low detection limits. We are currently further exploring how to make this operational as part of SmartWater4Europe (SmartWater4Europe 2014).

Dashboard

In order to make all this information easily available in the control room we further optimized our control room dashboard (Figure 2). In this dashboard, customer information (i.e. hospitals, factories), sensor data from treatment plants and sensor data in the distribution are displayed. In addition, call centre information, social media, and emergency response units (incl. fire department) are displayed. Every symbol is click-able and will display more information in the form of a short description, phone number, Twitter account or graph from a sensor. This way the operator can quickly asses how big the impact is and/or draw conclusion on the type of event that is taking place.

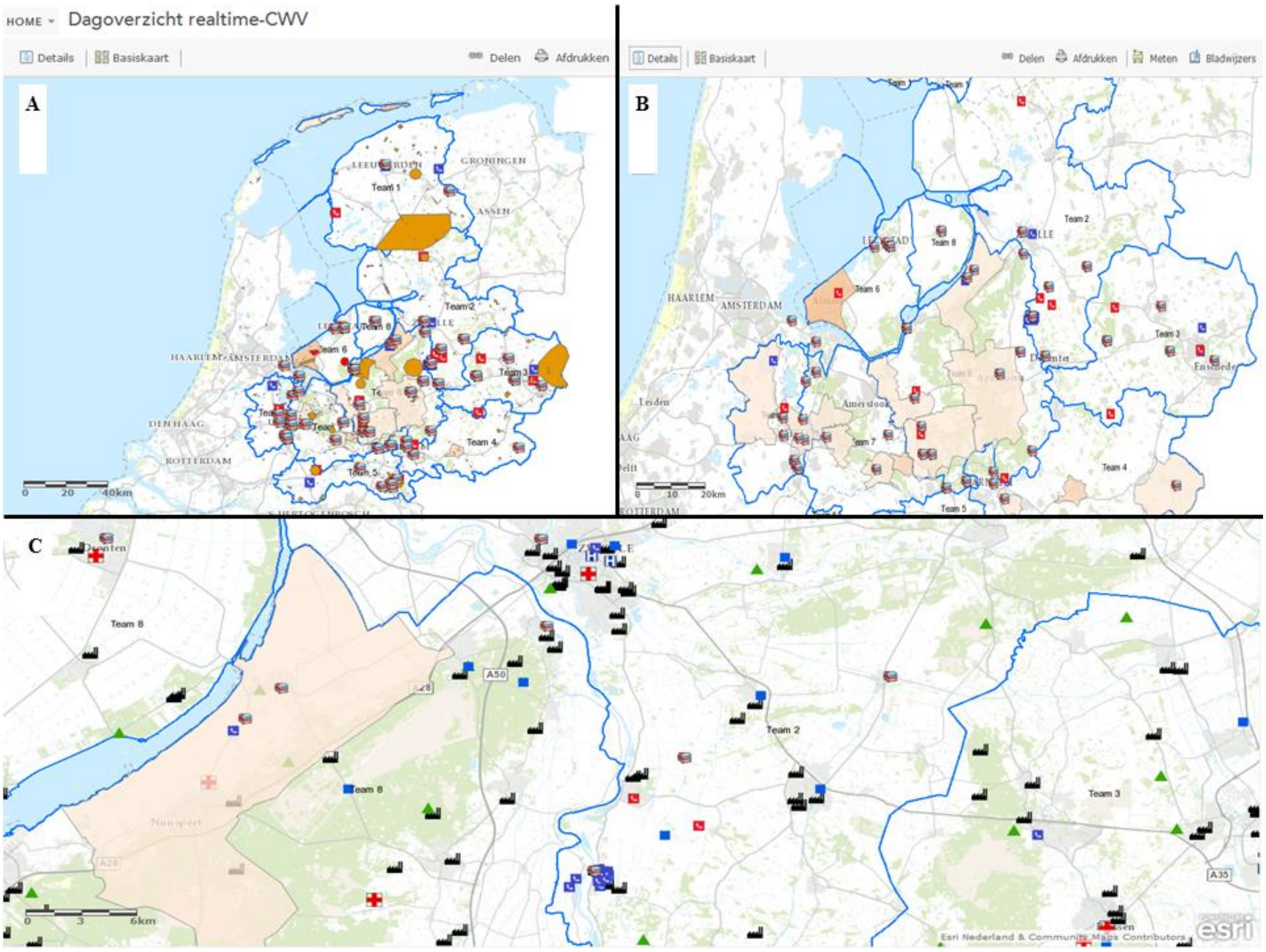

Figure 2. A. An overview of the Vitens supply area. In this picture, phone calls, social media, emergency response messages (incl. fire department), a leak monitor inside the DMAs (light pink) and customer impact zones are displayed (darker brown). **B.** This is similar to A, but a close up, here deviation in consumption (due to a holiday) in the DMAs can be better seen. **C.** The dashboard is more zoomed in, social media (blue squared), missed and answered call center phone calls (red phone symbol), Vitens infrastructure (green triangle), larger industries (black industry symbol) and hospitals (red cross) are displayed. Every symbol is clickable and has more information hidden, such as graphs and contact information.

RESPONSE STRATEGY

We confirm water quality changes through laboratory grab samples, 24-48 hours after the event occurred, as this is the time needed to transport and analyze the sample. If a water quality change is confirmed we currently inform all our customers (large industries and residential customers) in a similar matter at the same time.

To fully exploit real-time event detection and classification using sensor data, a different response strategy is required compared to the old situation where grab sample analysis provided the information (Thienen *et al* 2014, Thienen *et al* 2016). Firstly, the longer you wait with responding to a sensor signal, the more redundant your sensor network is going to be, waiting with a response as we currently do (>24 hours) the efficiency of the sensor network drops to <2% in preventing a contamination to reach customers (Thienen *et al* 2016).

Secondly, an unexpected change in the hardness might not necessitate notification of general customers (households), but could require swift and accurate informing of industries or critical customers such as hospitals. We asked several of these customers in the VIP/FL what they would like to know. Summarized they like to know 1) the exact time the water quality change reaches them 2) how long the event takes 3) the extent of the water quality change.

A first step into moving towards sharing this detailed information we have set up a nationwide website (in collaboration with other Dutch drinking water utilities) where maintenance, events and other water related issues are displayed (Figure 3). In addition, we ask our customers to sign up to our emergency push service to receive an e-mail, text messages, WhatsApp and/or Facebook message when the delivery of water is not to our standard in their zip code.

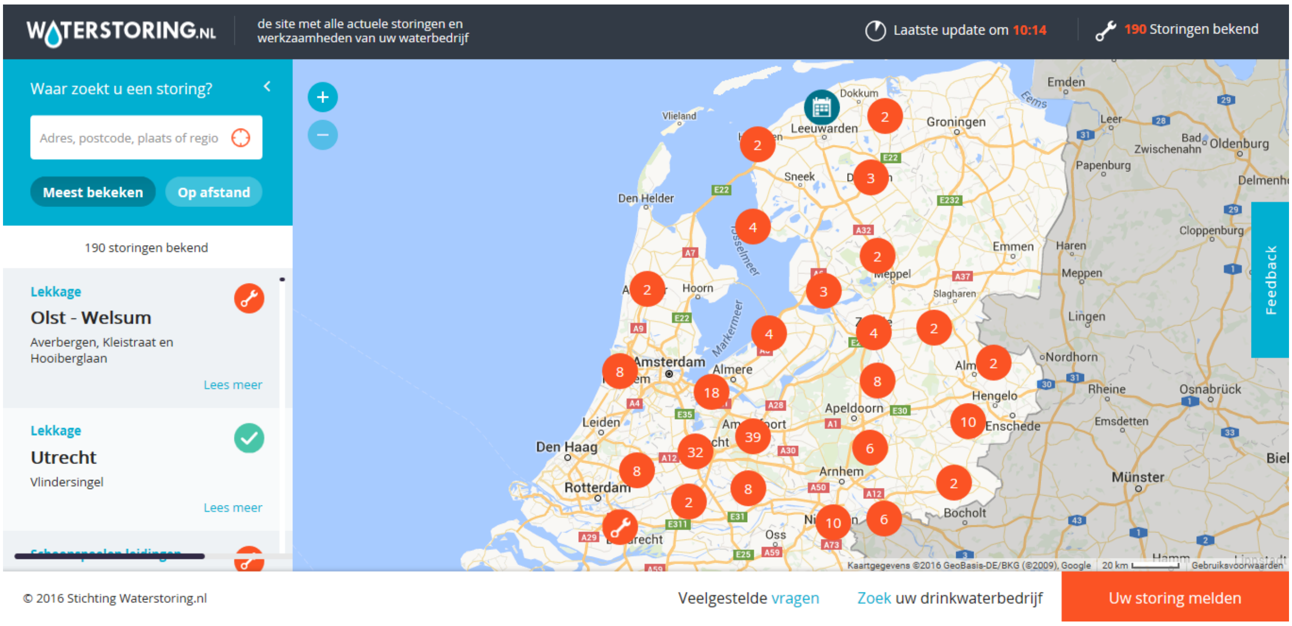

Figure 3. Screenshot of the nationwide website displaying all maintenance, events and other drinking water related issues.

SMART WATER GRID

Throughout the years we have demonstrated by using a stepwise approach a drinking water company can implement a smart water grid. The subsequent steps include setting up technical requirements (Tangena *et al* 2010), laboratory testing (Tangena *et al* 2010, Wijlen *et al* 2011, IJszenga Unpublished), small scale real-life testing (de Graaf *et al* 2012, Williamson *et al* 2014, IJszenga Unpublished), and large scale implementation (Williamson *et al* 2014, SmartWater4Europe 2014). The final step, taking the grid operational, set up installation and maintenance requirements and plans, implement event classification and define and use new response strategies. In this paper we presented the first practical information and challenges on this operationalization of the smart water grid, which can be used by other drinking water companies to form their own business case.

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