SAFEWATER – Application and Results of Innovative Tools for the Detection and Mitigation of CBRN- related Contamination Events in Drinking Water Supply Systems

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ABSTRACT

The security of drinking water is increasingly recognized as a major challenge for municipalities and water utilities. The safety and or security of drinking water can be threatened by natural disasters, accidents or malevolent attacks. The European FP7 project SAFEWATER (10/2013 - 12/2016) developed a comprehensive event detection and event management solution for drinking water security management and mitigation against major deliberate, accidental or natural CBRN related contaminations. The aim of this paper is to present the main results of the SAFEWATER project with a focus on (1) new sensors for detection of chemical, biological and radiological threats, (2) Event Detection System and (3) results of real-life user-case scenarios which have been investigated at three water utilities.

Keywords: drinking water networks, CBRN sensors, real-time event detection, event management, online simulation

1 BACKGROUND

The security of drinking water is increasingly recognized as a major challenge for municipalities and water utilities. The safety and/or security of drinking water can be threatened by natural disasters, accidents or malevolent attacks. In the event of a contamination, the contaminant will often spread in the water system rapidly and extensively before the problem is detected. Contaminated drinking water can lead to fatalities, induce major epidemics, disrupt economic life and create mass panic. A first generation of software packages and sensors have been developed prior to SAFEWATER for managing drinking water safety and security and in particular to detect incidents. However these first generation tools suffer from a range of serious shortcomings: (1) the set of available CBRN sensors, which are capable of detecting contamination threats to water drinking quality, is very limited; (2) real-time detection and alarm capabilities are non-existing or insufficient; (3) offline and online simulators are currently difficult to use for crisis management as the simulators are not integrated in a holistic platform and corresponding workflows; (4) online simulators for response, mitigation and recovery are almost nonexistent for real world systems at present; (5) there is currently no Event Management System available on the market which provides a user interface for the decision makers, which connects all software components and which provides all relevant information in a web based geographical information system (GIS).

The European FP7 project SAFEWATER [1] developed a comprehensive event detection and event management solution for drinking water security management and mitigation against major deliberate, accidental or natural CBRN related contaminations. provides an overview of the structure of the SAFEWATER system. The key module is the Event Management System (EMS) which handles incoming events and provides decision support in case of a crisis (as well as for routine operations). The Event Detection System (EDS) breaks ground by detecting potentially dangerous constellations of water quality parameters. These constellations may indicate a contamination of the drinking water network, or a so-far unknown operational effect. In case of an event it is important to quickly provide decision support regarding the best mitigation measures (e.g. opening/closing of valves). In case of an event, online response tools can predict the spread of the contamination and calculate optimal measures to minimize the impact of the contamination. The simulators can also be used in an offline context in order to train the operational staff. Furthermore, the simulators are used in order to train the event detection system. Within the SAFEWATER project, enhanced CBRN sensors are also developed which provide the ability for an early detection of CBRN contaminations. The aim of this paper is to present the main results of the SAFEWATER project with a focus on (1) new CBRN sensors for detection of chemical, biological and radiological threats, (2) Event Detection System and (3) results of real-life user-case scenarios which have been investigated at three water utilities. For details regarding the Event Management System (EMS) see [3]. Concept and results of the offline and online simulation tools are described in [4, 5].

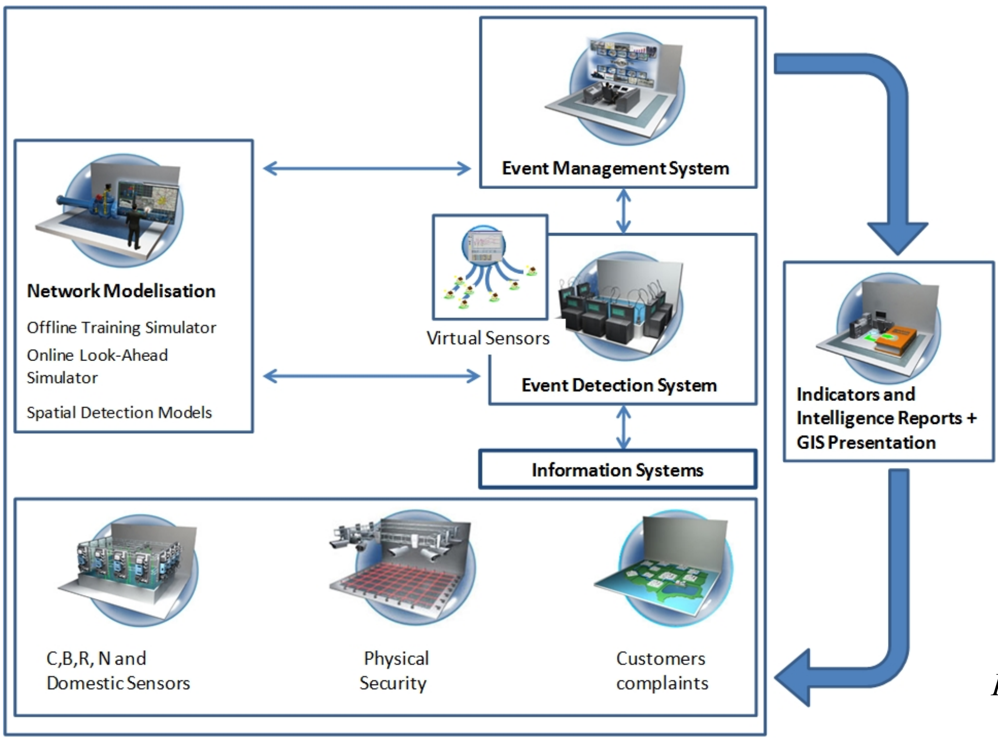


Figure 1: Structure of the SAFEWATER system

2 New CBRN Sensors

2.1 Sensor for Detection of *E.-Coli*

One common biological threat to drinking water is sewage contamination. Escherichia coli (E.coli) is used as a universal indicator bacterium for sewage since it is found in human and mammalian intestine and faeces and its presence in drinking water indicates contact of the water with sewage. In the SAFEWATER project, Acreo has developed an autonomous system for detection of E. coli in drinking water. This system is based on antibody based fluorescent labeling of E. coli bacteria, followed by optical detection of E. coli using a video based flow cytometer. The instrument takes in a water sample and mixes it with the fluorescent labeling agent and incubates it for 10 minutes at 39-40 °C to allow the fluorescent antibodies to bind to the surface of *E. coli* bacteria before the sample is pumped through the optical sensor that records the now fluorescent bacteria. The optical data is collected by a video camera, and after signal processing the approximate number of *bacteria/ml* is established.

The instrument (Figure 2, left) can work autonomously, making measurements up to two times per hour for weeks, until it is necessary to refill reagents. The results are transferred via regular SCADA systems (4-20 mA signal, ModBus or GSM).

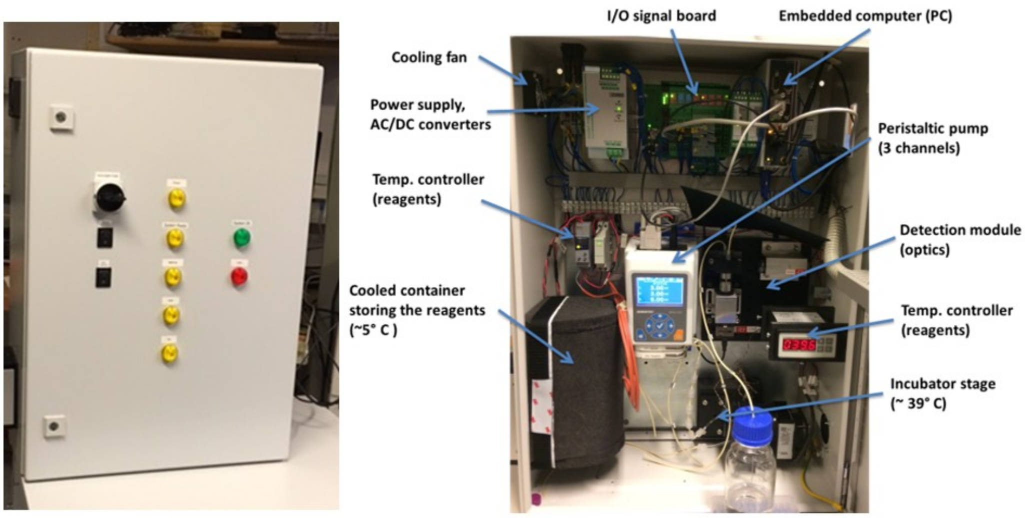


Figure 2: E. coli sensor (left) and the functional parts of the E. Coli sensor (right)

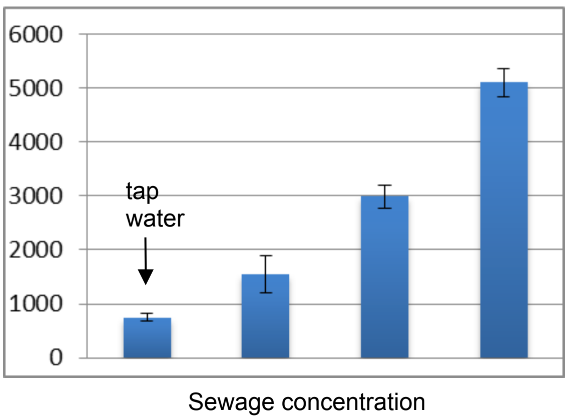


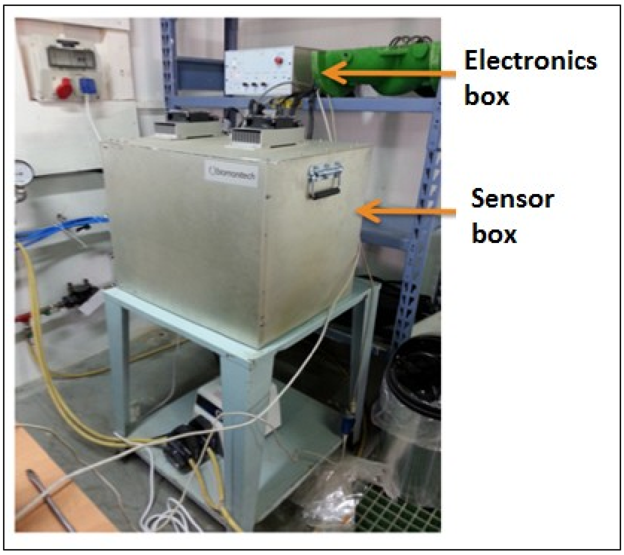
Figure 3: Counted E. coli bacteria. Demonstration of dose response when increasing amount of sewage was added to tap water. The first column from left is pure tap water, followed by increasing mix in of pre-sedimented sewage.

The sensor has been tested at water facilities in Jerusalem (HaGihon), and in Zurich (WVZ). Examplary results are shown in Figure 2Error: Reference source not found. Here, either pure tap water, or tap water contaminated with small amounts of pre-sedimented sewage has been analyzed. As we can see, the pure tap water gives a low background signal, but increasing amount of sewage gives a proportionally increasing signal. Thus, it is possible to use the sensor as an early warning system. By using labeling agents with another specificity, this system can also be used for detection of bacteria other than *E. coli.*

2.2 Toxicity Sensor based on Bioluminescence

Commonly used chemical analysers can detect and identify a restricted number of substances. Numerous other contaminants may occur, that cannot be detected and/or that may have unknown toxic properties (there are more than 87,000 chemicals used in the USA). This is why biological early warning systems such as those utilizing luminescent bacteria offer the potential to monitor a truly wide spectrum of dangerous contaminants, even those that escape conventional analytical monitoring. Currently, there are several players in this market, e.g. MicroLan (The Netherlands); Modern Water (UK); Applitek (Belgium). All these sensor systems are based on the same bioassay-utilizing Vibrio fischeri and sodium chloride solution. This method has limited sensitivity when used to test drinking water quality.

Biomonitech's has developed an online sensor (BMT200) utilizing *luminescent bacteria* as sensitive sensors for drinking water toxicity. Changes in light level reflect degree of toxicity. The sensor utilizes a technology that does not look for specific contaminants; it is therefore effective also for detecting chemicals that are not expected to be found in the water. The bacteria are sensitized to low concentrations of a broad rage of chemical toxicants by using proprietary assay buffers: One that sensitizes the bacteria to cationic heavy metals and metalloids, the other to (mainly) organic toxicants, see Error: Reference source not found (right) for example of discriminatory response. The development process and design committed to reducing the manufacturing costs, minimizing moving parts, stabilizing the biotechnological core (the bacteria's light level under weeks-long continuous operating conditions). The sensor has been tested at water utility HaGihon (Figure 1, left).



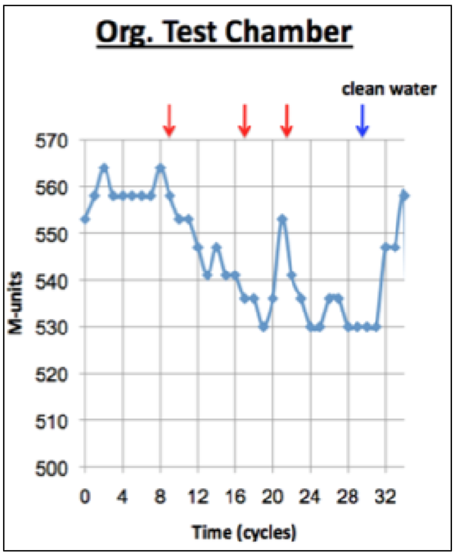


Figure 4: Left: Sensor prototype version deployed in HaGihon (Jerusalem), right: Response to various concentrations of the organic herbicide 2,4-D (Xppm, 2Xppm, 3Xppm – marked with red arrows; spiked into local Israeli mineral water) in the two assay chambers

BMT200 continuously monitors the presence of chemical contamination in drinking water. Concentrations of contaminants are reported within 15 minutes (either over a web frontend or via serial ModBus linked to SCADA). BMT200 connects through a bypass to an inlet water line, continuously drawing water samples at a rate of four per hour. Once toxicity is detected, the suspected sample is drained into a “grab sample container” for further off-line analysis. The sensor adapts to the local water quality of the site in which it is installed, and is not sensitive to normal seasonal and spatial water quality variations. The sensor is fully automatic, requiring attention once per month to refill reagents that feed the core biotechnology of the sensor.

2.3 Radioactivity Sensor

To manage the challenge of detecting alpha and beta radiation, CEA (France) has designed a new plastic scintillator light collection system and developed associated high velocity electronics and data processing algorithms. This new approach uses scintillating optical fibres as scintillator and optical guide, to come close to the bulk of the water, in order to increase the detection area. The scintillating fibres convert the radiation into light that travels through each optical fibre and is finally detected by the PMT (Photon Multiplier Tube). To do a measurement in water and online, the system needs to have a high sensitivity due to the small free path of particles (for alpha particles with an energy of 5 MeV, the free path is 37.2µm; for beta particles with an energy from 50keV to 2 MeV, the free path is contained between 43µm and 1 cm). The beta radiation sensitivity is linked to the active measurement volume and the alpha sensitivity is linked to the detector surface. So the sensitivity is globally linked to the number of scintillating optical fibres.

The system is composed of a sensor part (Error: Reference source not found) including a scintillating optical fibre bundle with its PMT (Photon Multiplier Tube) and an acquisition / processing unit including a display and an embedded computer. Error: Reference source not found shows the linearity of the detector response to detect alpha particle online. The sensitivity of the system could be enhanced by increasing the number of optical fibres in the system (increasing the active measurement volume).

Figure 5: Radioactivity Sensor (CEA)

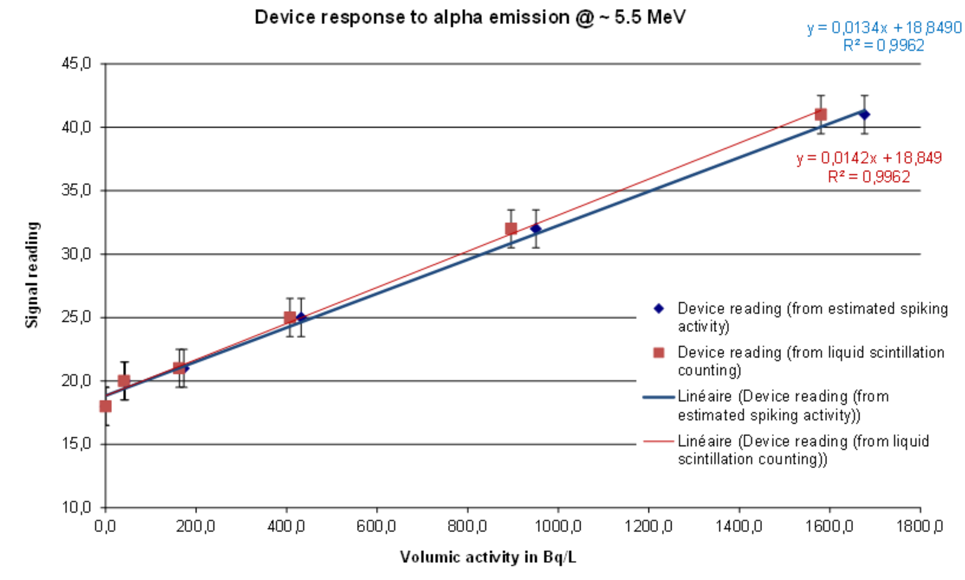


Figure 6: System response for alpha contamination

3 Event Detection System

The Event Detection System (EDS) is a term coined by the EPA (Environmental Protection Agency, U.S.) for a software system which can detect a water quality event before it turns into a critical problem. A typical EDS system is based on non-supervised machine learning algorithms. The need to practice a non-supervised algorithm comes from the nature of water distribution systems. In such systems, *True Events* which involve acidents or deliberate man-made injection of contamination into the water are rare. Hence the need to learn what constitutes the common/normal situation and thus be able to detect the abnormal situations based on the knowledge of what is normal.

The EDS which has been developed by Decision Makers Ltd. is based on several algorithms. Each algorithm is called a *Detector* and is designed to perform a specific task. Detectors are grouped into four basic groups:

- Group 1: Single sensor algorithms. Algorithms which learn the statistical limit, trend and rate of change of each variable separately. A violation of each of the learned limits generates an alarm after an appropriate delay time.
- Group 2: Multi sensor algorithms. Automatic building of density functions of past combinations of sensor values. Using the density function, the EDS can detect rare combinations; also learning of the dynamics of value combinations is possible.
- Group 3: Rule-violation algorithms. Procedure for testing sensor values with a set of predefined engineering rules defined by the user.
- Group 4: Hazard similarity detection. These detectors identify when the water quality is approaching a combination that was classified in the past as a hazardous combination.

Each detector has a severity level and a delay time. When even a single detector triggers an alarm, an event is generated. An event may include several alarms. Events can be delegated to operators using email or SMS. They are also displayed in the SAFEWATER Event Management System.

Once an event has been dealt with, it should be classified by an authorized operator. Classification may be to one of the following: *True event*, *False Event*, *Ignore* (not to be used as a learning event) or *Other*. *True event* means that the operator confirms that triggering the alarm was justified. In the case of True Positive classification, detectors which triggered alarms are rewarded "Good points". *False Event* means that the operator rejects the decision of the EDS to trigger an alarm. Detectors which trigger such alarms are penalized with "Bad points". *Ignore* and *Other* classifications do not grant points to detectors. Ignore is used to classify non-important events (e.g. some test). Other is used to document events which are not used for the learning process but are important from managerial point of view. Over time, detectors with "Bad points" should be calibrated. Thresholds should be increased and/or delay time should be extended, until the specific detector stops gaining bad points.

The EDS has been implemented, tested and evaluated at all three SAFEWATER water utilities (HaGihon - Jerusalem, WVZ – Zurich and AdA - Portugal) [1].

4 Use Cases

Use Cases in the SafeWater project were designed to guide the SAFEWATER solution by setting up a number of real-life scenarios of contamination events likely to challenge municipal water supply systems. The use case scenarios were later used to test the effectiveness of the SAFEWATER solution components in dealing effectively with the use cases.

4.1 Detection of Contaminations at Water Utility HaGihon

One of the use cases of water utility HaGihon (Jerusalem) was defined as follows: *A major municipal water line operating under pressure and supplying a large section of a city is contaminated, as a result of a terror attack by pumping a water solution contaminated with a mixture of CBRN contaminants into the supply line*

Aspects of this use case were tested at the Beta-Site facility as well as in a large water supply demonstration area (DMA) within HaGihon's distribution system. The chemical, biological and radiation sensors were all installed in the Beta-Site and tested by running appropriate contaminants through the system and ascertaining the ability of the sensors to detect the contaminant on-line and to generate an immediate alarm. (Radioactive materials were used only at the CEA facility). HaGihon also installed several Low Energy (LE) water quality sensors in the DMA and ran simulation tests to establish the sensors' ability to detect abnormal turbidity and generate an alarm. The project included optimization of the number and location of LE sensors in the DMA, carried out by 3S Consult.

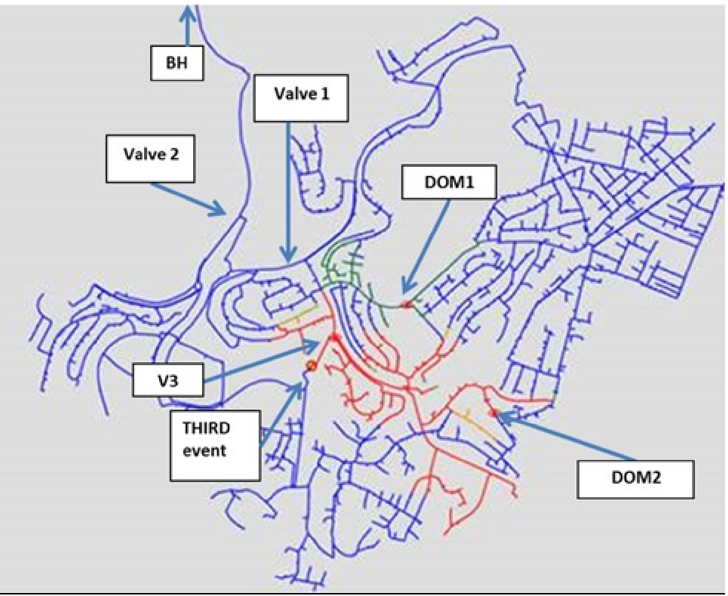


Figure 7: Map produced by the hydraulic dissemination model of a contamination event in HaGihon DMA. The dissemination of the contaminant according to concentrations is shown as different colours

A vital part of the SAFEWATER solution is the on-line hydraulic "*look ahead*" simulator developed by 3S Consult and Fraunhofer IOSB. This advanced tool allows an event manager to quickly examine how far and where a contaminant has dispersed in the distribution system, thus allowing the operator to take steps to halt the spread in near-real-time. HaGihon examined the simulator by running 6 contamination scenarios within the above DMA and ascertaining that the model could predict the contaminant dispersion (see exemplary result in Error: Reference source not found). Advanced features of the model include the capability to locate the possible point of contamination by examining the time-of-alarm produced by several sensors in the distribution system, as well as indicate which valves should be closed in the water distribution system in order to effectively halt the contaminant spread at a given time-after-introduction.

Another vital part of the SAFEWATER solution is the Event Mangement System (EMS) that incorporates a user-prompting menu for dealing with contamination events, including emphasis on the Public Relations aspect of such an event. Keeping in mind that Public Relations is at least as important as the engineering aspects of managing a contamination event, the EMS prompts the Event Manger to initiate press conferences, update key stakeholders, etc.

4.2 Test Network and Investigations at Water Utility Zurich

The test network located on the water utility WVZ premises in Zurich consists of 150 m pipe length in total and is 5 m wide (Figure 8 left). The test network has two long pipes and four different types of junctions to simulate a real water distribution network with several distinct flow conditions. A pump is installed to dose a contamination within a range of 100 to 12’000 mL/h. As general detection system, five multi parameter probes from Intellitect™ are installed, which can be inserted at any of the available quality measurement locations (“QM” in Figure 8 right).

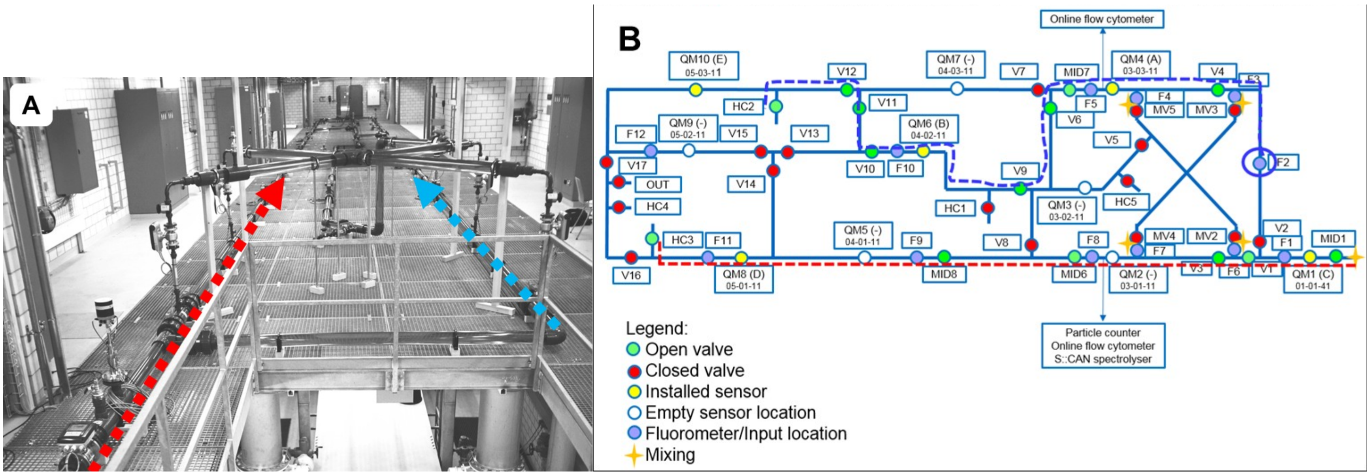


Figure 8: Left: Picture of the test network with indicated contanmination and clean water branch. Right: Setup of the test network during the contamination experiment. The blue dashed line shows the flow path of the clean reference water in the upper part of the test network while the red dashed line shows the flow path of the contaminated water in the bottom part. The blue circle around F2 indicates the second input location for drinking water.

A realistic contamination scenario with different concentrations of sewage contamination was performed at the test network in order to evaluate the detectability of a sewage contamination in a drinking water network. Actual pre-treated waste water from the nearby waste water treatment plant was added to the drinking water of the main branch in the test network. A second branch of the test network, fed by clean tap water, allows to distinguish between fluctuations of the parameters due to changes in the tap water compared to changes due to contamination. Prefiltered sewage was injected close to the inlet to reach three different concentrations of sewage in the system: 0.1%, 0.3%, and 0.5%. Multiparameter probes measuring pH, oxidation-reduction potential (ORP), conductivity, dissolved oxygen (DO) and temperature. Water particle counter measuring particle down to a size of 1 µm. Spectrolyser measuring the adsorbance at 256 different wavelengths ranging from 190 to 720 nm. Online bacterial analyser measuring the total cell count (TCC) and high/low nucleic acid content of each individual cell. The resluts clearly show that some of the classical parameters, like pH, ORP and conductivity are unsuitable to detect sewage contamination, while the particle values of the contaminated branch change by up to 6000% (!) in comparison to the uncontaminated tap water. Most of the parameters measured by the Intellitect probe either show no or insignificant differences between the contaminated and uncontaminated branch (maximum 4% difference). This is the case for all except the dissolved oxygen content, which has a difference of up to 12%. It needs to be mentioned that the amount of dissolved oxygen in the distribution network of WVZ fluctuates depending on the water source. The groundwater has an oxygen content of approximately 10 mg/L. In comparison, the treated lake water has a higher oxygen content of about 15 mg/L because of its double treatment with ozone. Therefore, the amount of dissolved oxygen in drinking water from Zurich can naturally fluctuate by up to 30%. The S::CAN spectrolyser with its adsorbance measured at 256 wavelengths can clearly detect the addition of sewage down to 0.1%. The online bacteria analyser (OBA) measures a difference of up to 1400% for TCC and 7000% for HNA between tap water and contaminated tap water.

5 CONCLUSIONS

Within this paper we have presented the main results of the SAFEWATER project with a focus on (1) new sensors for detection of chemical, biological and radiological threats, (2) Event Detection System and (3) results of real-life user-case scenarios which have been investigated at three water utilities (HaGihon - Jerusalem, WVZ – Zurich and AdA - Portugal). The features and functionality of the SAFEWATER solution has been demonstrated in a live demo at a test network of water utility WVZ (Zurich) in 11/2016. In the future it is planned to install and enhance the SAFEWATER solution at further water utilities.

Acknowledgements

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