Analog Integrated Circuits and Signal Processing (2018) 96:327–335
https://doi.org/10.1007/s10470-018-1143-3

Use of the smart technology for water quality control: feedback from large-scale experimentation

Christine Saab[1,3] · **Elias Farah**[1] · **Isam Shahrour**[1,2] · **Fadi Hage Chehade**[3] · **Sana Ounaies**[1]

Received: 26 October 2017 / Revised: 19 February 2018 / Accepted: 23 February 2018 / Published online: 6 March 2018

Abstract

The main purpose of drinking water network is to ensure safe quality of water to users. However, accidental contamination and malicious attacks in water networks can degrade the water quality. Such critical events threat the human health and lead to harmful diseases. Water utilities are concerned by the control of water quality. Since conventional methods based on laboratory analyses require several days, online control technology presents good opportunity to rapid detection of any water contamination. Devices based on smart technology have been developed for real-time control of the water quality. However, the use of these devices is recent and yet requires investigations. This paper presents feedback of the use of the smart technology in a large-scale experimentation conducted at the campus of Lille University within the European project "SmartWater4Europe". Two devices are used: S::CAN, which measures various parameters such as Conductivity and Turbidity and EventLab, which measures the variation of the refractive index. This paper presents the implementation of these devices, data storage and management as well as analysis of recorded data.

Keywords Water quality · Smart technology · Sensors · Online monitoring

1 Introduction

The main objective of the water supply is to provide good quality of drinking water to consumers. Water distribution networks are not inert transport systems. The quality of water produced at the water treatment is subject to a complex physical, chemical and biological interactions during water transport [1]. In addition to intentional contamination, accidental contamination could occur in Water Distribution System (WDS) by backflow, networks interventions and repair actions. The consumption of contaminated drinking water could be very dangerous on human health. Recently, a contamination by a chemical industry (MCHM) occurred in the distribution networks of Charleston, West Virginia (USA) and affected more than 300,000 consumers [2]. In general, water quality is analyzed in laboratory using water samples from different locations in the network. Laboratory analyses include (1) physico-chemical analyses that determine organoleptic characteristics of water (color, odor, etc.) and (2) microbiological analyses that identify the presence of pathogenic microorganisms. These methods require long delay compared to real-time control (from several hours to many days).

Water utilities are concerned by the development of new technology for early detection of water contamination. A rapid identification of the contamination reduces the harmful impact on human health. The security of water network can be enhanced by the implementation of smart technology, which allows real-time monitoring of water quality in WDS. However, the use of smart technology in water quality control is recent and yet requires investigations. This paper presents feedback of the use of the smart technology in a large-scale experimentation, which is conducted at Lille University campus within the European project "SmartWater4Europe".

✉ Christine Saab
christine.saab@hotmail.com

[1] Laboratory of Civil Engineering and Geo-Environment, University of Lille, 59650 Villeneuve d'Ascq, France

[2] School of Civil Engineering, Tongji University, Shanghai 200092, China

[3] Civil Engineering Department, Doctoral School of Sciences and Technology, Lebanese University, Beirut, Lebanon

2 Smart water system for water quality control at the Scientific Campus of Lille University

Figure 1 presents the smart water system used for water quality control at the Scientific campus of Lille University. It includes installation of the smart devices (S::CAN and EventLab), data transmission, storage and analysis as well as comparaison of smart meters data with laboratory tests. Within an academic partnership, the investment cost for each unit is about 20,000 Euros.

2.1 Water quality sensors

2.1.1 S::CAN

S::CAN micro::station is a water quality sensor that conducts an online monitoring of multiple parameters. The main components-spectro::lyser, sensors and controller-are assembled with required flow cells, mounting fittings and pipework on a compact panel [3]. Different elements constitute the micro::station [4]:

- Con::cube controller with moni::tool software for the acquisition and display of data and for station control.
- Flow cell with auto brush cleaning device to provide cleaning of the optical measuring windows.
- System tubing included in the panel assembly.
- Flow detector that give alarm if the flow decreases below 0.25 L/min. The recommended flow is about 0.5 L/min.
- Inlet strainer that avoid the entrance of coarse material in the station.
- Pressure transmitter that supply the pressure signal to the con::cube.
- Main panel that assemble all components.
- Flow restrictor for automatic flow restriction and backflow prevention in by-pass.
- Probes ensuring continuous monitoring of water quality parameters.

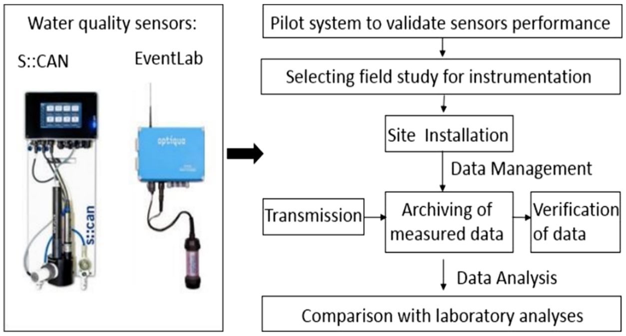

Fig. 1 Methodology used in the Large-Scale experimentation

The four main probe that provide data every minute are:

- i::scan ensures measurement of the absorbance UV254, the TOC (Total Organic Carbon) and DOC (Dissolved Organic Carbon) as indicators of the amount of organic substances, the turbidity (EPA & ISO) that indicates the presence of microorganisms (bacteria, virus, etc.), the temperature shown by a bad flavor or odor and the color as organoleptic indicator.
- pH::lyser measures pH value for the corrosion control and the temperature.
- Chlori::lyser measures the amount of free chlorine as indicator of biofilm growth.
- Condu::lyser allows measurement of Conductivity as indicator of the water mineralization and the temperature.

A reference line is obtained for each parameter in case of normal drinking water. An abnormal quality of water induces significant deviation from the reference line. Such variation should be analyzed to identify the potential existence of contaminants. S::CAN uses 3G SIM card for data transmission to a server, which can be connected to a Supervisory Control and Data Acquisition (SCADA) system. OpenVPN and IP address are used to access S::CAN server. A web browser (Chrome, Mozilla, etc.) is needed for access to real-time and historical data. Output can be downloaded in csv files. All options of con::cube can be controlled remotely through VPN connection.

2.1.2 Optiqua EventLab

EventLab records the variation of the refractive index (RI). Any substance dissolved in water affects this index [5]. The use of RI has a number of advantages for water quality monitoring and the detection of water quality incidents [6]:

- The only generic parameter available: detect all chemical changes, irrespective of their nature, while others sensors are sensitive only to a part of the spectrum of contaminants.
- Consistency in response: the consistence sensitivity of EventLab allows an estimation of the order of magnitude of a contamination event.
- Response linear with concentration: a linear relationship is maintained between RI and the concentration of contaminant [7].
- High resistance to matrix interference: with RI, there is no dependence on matrix effects. The only factor that can affect the RI is the temperature. Its effects is fully accounted for in the compensation mechanism of EventLab system.

The generic Optiqua EventLab sensor operates at a sensitivity level equivalent to parts per million (ppm) levels for any chemical contaminant [8]. It does not require any reagents or high cost of maintenance. This sensor is controlled via a web server using 3G SIM card. Data are displayed in real-time through Optiqua website and can be collected in csv files.

The system is based on the Mach–Zehnder Interferometer (MZI) principle as illustrated in Fig. 2. The basic layout of the MZI consists in an input channel wave-guide that splits into two identical branches, which are then combined again to form the output wave-guide [9].

The main output signal of EventLab is the variation of phase $\Delta\Phi_{m\ (measured)}$ of light propagating over the interaction window, given by the following equation [7]:

$$\Delta\Phi_m = (2\pi/\lambda)\, L_{\mathrm{int}} \left(\partial n_{eff}/\partial n_{water}\right) \Delta n_{water} [radians] \tag{1}$$

where λ is the wavelength of the light in vacuum, L_{int} is the interaction light of the sensing window, $\partial n_{eff}/\partial n_{water} = 0.21$ and Δn_{water} is the refractive index change in the water. With $\lambda = 850$ nm and $L_{int} = 10$ mm and using (1), the refractive index change Δn_{water} is given by:

$$\Delta n_{water} = 4 * 10^{-4} (\Delta\Phi_m/2\pi) \tag{2}$$

In addition to the phase, EventLab measures continuously:

- Temperature based on Resistance Temperature Detector (RTD).
- Signal health and signal level as indicators of probe status and the need of maintenance.
- Response which is the phase corrected after taken into consideration the effect of temperature.
- F24 Response which indicates how much a response value is above or below the average of the preceding 24 h.

Since the use of these devices is recent, recorded data do not yet allow us to determine threshold limit values for water contamination. However, these devices allow to detect the occurrence of upnormal events by the deviation from recorded baseline. Additional analyses are necessary to determine the origin of these events.

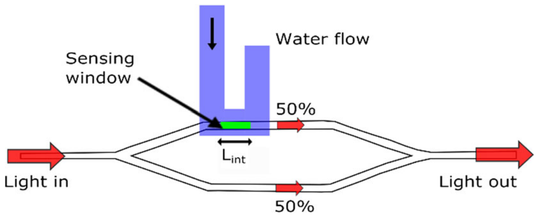

Fig. 2 Basic layout of the Optiqua MZI sensor [5]

2.2 Data management

Recorded data are archived and analysed using PI system, which collects, stores and manages data. Figure 3 illustrates a typical diagram for PI system components. Through PI interface nodes, information collected from data source, are stored in PI tags on data archive. Access to data is done either directly from data archive or from AF (Asset Framework) server [10].

According to recorded data, 13 tags have been created for S::CAN sensor: UV254, Turbidity ISO, Turbidity EPA, TOC, Temperature1 (probe i::scan), Temperature2 (probe Condu::lyser), T10, R alarm, pH, Free Chlorine, Flow, Conductivity and Color. In the same way, for EventLab sensor, 13 tags have been created for the following parameters: algorithms A1Res, A2Res, A3Res, DetectorA1, DetectorA2 and DetectorA3, then F24 Response, phase, Response, signal health, signal level and Temperature. PI Datalink, a Microsoft excel add-in, is used to report data and then analyse the results.

2.3 Data verification

The smart water quality system could suffer from faults related to sensors or to data transmission. S::CAN indicates “Error” when measurement in a time step is missed. In case of absence of data, an alert is generated to analyze and solve the problem of lost. Figure 4 illustrates a case of data loss due to measurement interruption in May 29, 2017 between 16:17 and 16:59.

It is important to identify “unexpected values”, which could result from system faults. Two methods could be used for this identification:

- Outlier: a significant deviation, generally due to noise in SCADA system at a single time step. Such instantaneous variation should not generate alarm. This value is defined as “out of range” from expected data.

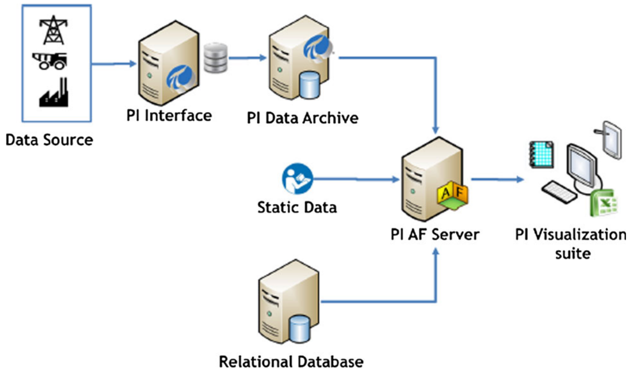

Fig. 3 Diagram of the components of a typical PI system [10]

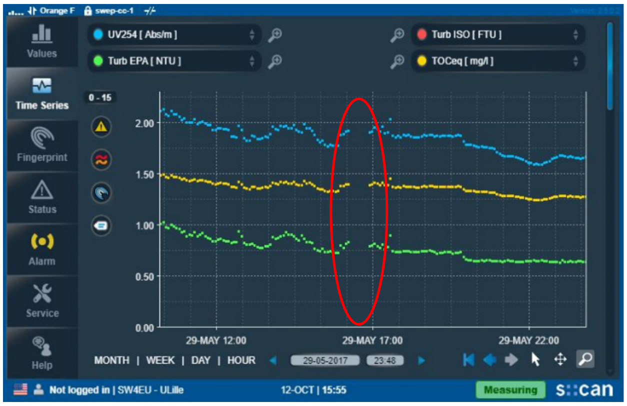

Fig. 4 Lost of S::CAN data at Polytech'Lille in May 29, 2017

- Event: significant deviation, from expected signal, that remains for a period of time steps. It can be defined as a group of unaccepted values that exceed normal thresholds. Such variation should generate an alarm.

3 Large-scale experimentation

3.1 Site description

The large-scale experimentation is conducted at the Scientific campus of Lille University. The campus stands for a small town with around 25,000 users. It includes 150 buildings and 100 km of urban networks (electrical network, sewage and heating, drinking water). The water distribution network is composed of 15 km of cast iron pipes which have diameter between 20 and 30 mm (Fig. 5). The network includes 49 hydrants, 250 isolations valves, purges and stabilizers [11]. The water is supplied to the campus at five sections.

3.2 Water quality devices installation

S::CAN and EventLab were installed in two steps. The first installation was conducted in April 2016 at the Engineering School Polytech'Lille, while the second was conducted in October 2016 at Barrois restaurant. At both locations, devices were installed in the technical room. A derivation from the nearest pipeline was used for the devices supply. Water samples used by the devices passe through an evacuation system. Power supply for sensors is ensured from the technical room electricity. Figure 5 illustrates the location of the devices installations.

The use of these devices required maintenance and cleaning. For S::CAN, the procedure requires the use of distilled water and sometimes other liquids such as Ethanol and Isopropanol. In particular, the cleaning of Chlori::lyser requires the use of specific materials (Gel-Electrolyte-E507) and plastic sheet. For EventLab, maintenance is required when the signal health and signal level drop below 0.15. The cleaning of sensing windows requires the use of cleaning agent, Polyurethane swab and drinking water. Depending on the local water quality, the signal strength could deteriorate; a filter unit should be used to capture large particles.

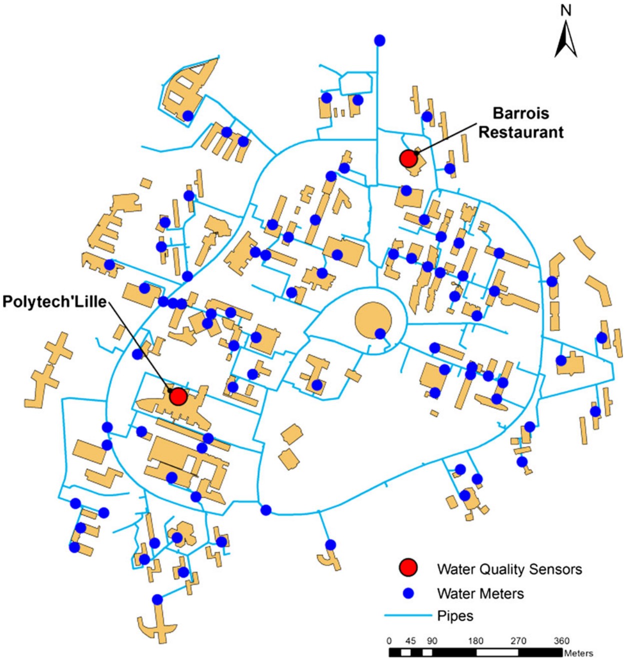

Fig. 5 Water distribution network of the campus with the locations of sensors

4 Water quality analysis

4.1 S::CAN recorded data

Figure 6 shows an example of data recorded by S::CAN at Barrois Restaurant during the period December 1 and 15, 2016. The figure shows also the threshold limits according to the World Health Organization (WHO) standards. Since the recorded data are below the standards thresholds, this example indicates a safe drinking water condition.

Figure 7 shows data collected by S::CAN at Polytech'Lille during the period September 1 and 15, 2016. Some events are detected. They are characterized by an abnormal increase regarding the reference line. These events are generally observed in morning. During night, the consumption is lower and signals remain stable. Figure 7 displays also the variation of hydraulic parameters: pressure and consumption. We observe that an increase in the water consumption is correlated with the peak of some

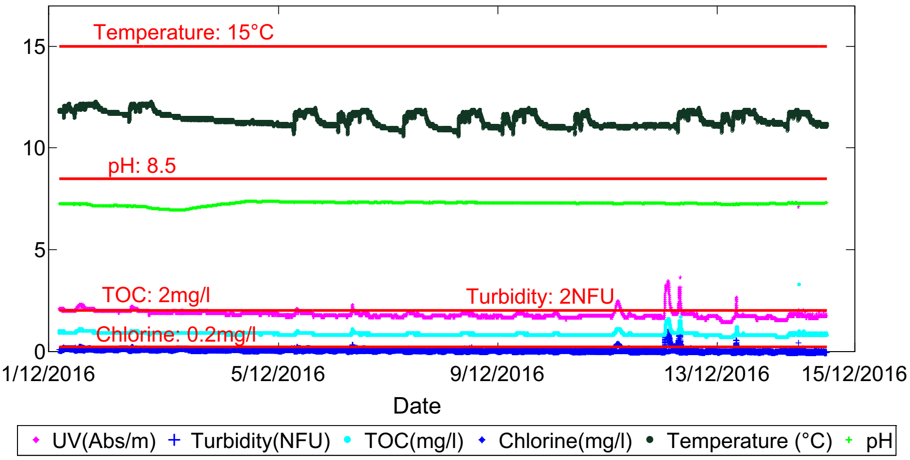

Fig. 6 S::CAN response with standards thresholds between December 1 and 15, 2016 at Barrois

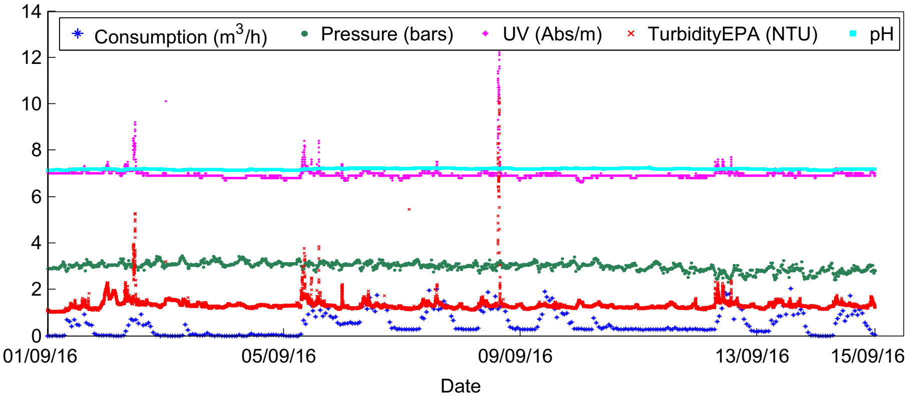

Fig. 7 S::CAN response with hydraulic parameters between September 1 and 15, 2016 at Polytech'Lille

water quality parameters. The increase in the signals of UV and Turbidity indicates the presence of suspended materials that disturb the water quality. This change in the water quality could result from the extraction of particles from the aging water pipes when the water flow increases. Deposits release from water pipes is illustrated by the sudden increase in UV and Turbidity.

4.2 EventLab recorded data

Figure 8 shows an example of data recorded by EventLab at Polytech'Lille on July 1, 2016. It shows the variation of phase for the recorded data. We observe that this variation is below limit values. However, some events are detected outside the thresholds (red circle in Fig. 8). To identify the source of such events, the consumption is displayed in the same graph. A sudden increase in water consumption is followed directly by a significant deviation in the phase variation. As indicated earlier, this change in the water

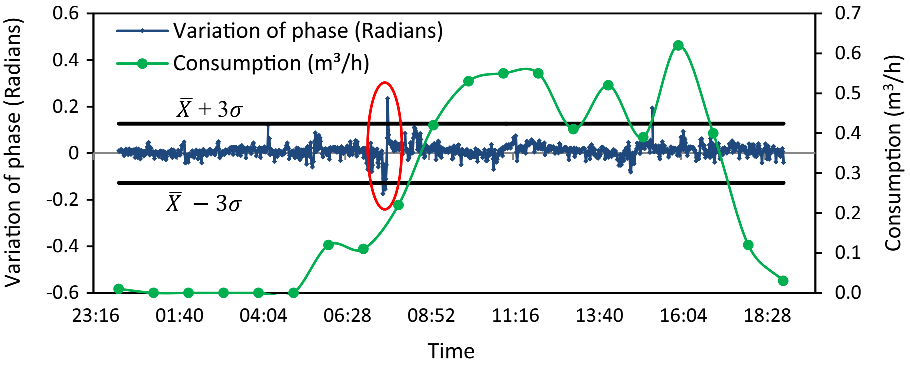

Fig. 8 EventLab response with consumption profile on July 1, 2016

quality could result from the extraction of particules from the aging water pipes when the water flow increases.

4.3 Comparaison with laboratory water quality analyses

Data recorded by S::CAN were compared to laboratory analyses conducted on water samples collected at two locations on February 7 and 27, 2017. Laboratory tests included:

- Microbiological analysis concerning microorganisms such as Escherichia Coli and Intestinal Enterococci. The presence of micoorganisms is directly correlated with a low amount of free chlorine induced generally by biofilm growth.
- Physico-chemical analyses concerning TOC, DOC, pH, turbidity, absorbance UV 254, and conductivity.
- Total and free chlorine
- Anions tests concerning Nitrates and Sulfates.
- Cations tests concerning Sodium and Ammonium.
- Metals tests concerning Aluminum, Iron, Arsenic, Copper and Manganese.

Figure 9 shows a comparison of S::CAN records and laboratory analyses. The relative error is calculated as follows:

$$Error(\%) = \frac{|Sensor\ data - Laboratory\ data|}{Laboratory\ data} * 100 \qquad (3)$$

Results of comparison indicate:

- A good agreement between S::CAN data and laboratory results for some parameters such as pH and temperature (error less than 3%).
- Significant error for parameters such as chlorine and DOC (error between 27 and 47%).

4.4 Calibration

In order to reduce the gap between S::CAN and laboratory data, a calibration adjustment is applied:

- For conductivity and free chlorine, we calculate the correction factor: quotient between laboratory and S::CAN data. Table 1a indicates an average factor of 1.2 for chlorine at Polytech'Lille.
- For i::scan parameters (turbidity, TOC, DOC), we calculate the corresponding offset: difference between laboratory and S::CAN data. Table 1b shows an average offset of 0.55 for DOC at Barrois.

After calibration, S::CAN data becomes closer to laboratory results. An example is illustrated in Fig. 10. The

Fig. 9 Laboratory comparison. **a** Polytech'Lille; **b** Barrois

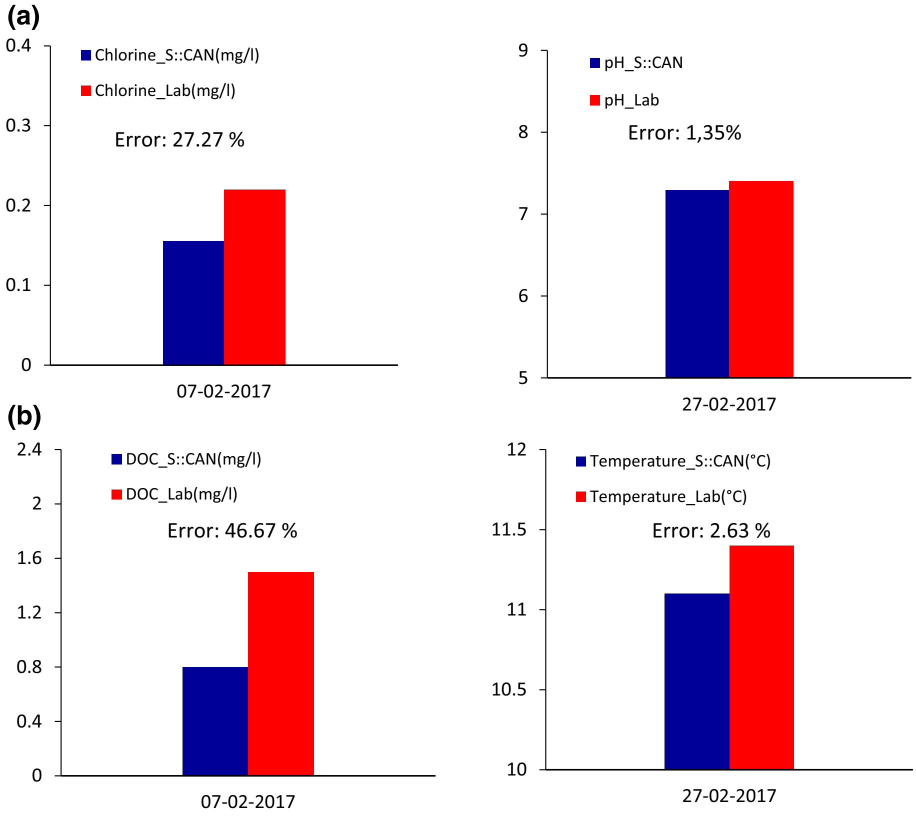

Table 1 Adjustments calculation

Date	S::CAN	Laboratory	Factor
(a) Chlorine_Polytech (mg/L)			
07/02/2017	0.16	0.22	1.4
27/02/2017	0.15	0.16	1.1
Average			1.2
Date	S::CAN	Laboratory	Offset
(b) DOC_Barrois (mg/L)			
07/02/2017	0.8	1.5	0.7
27/02/2017	0.9	1.3	0.4
Average			0.55

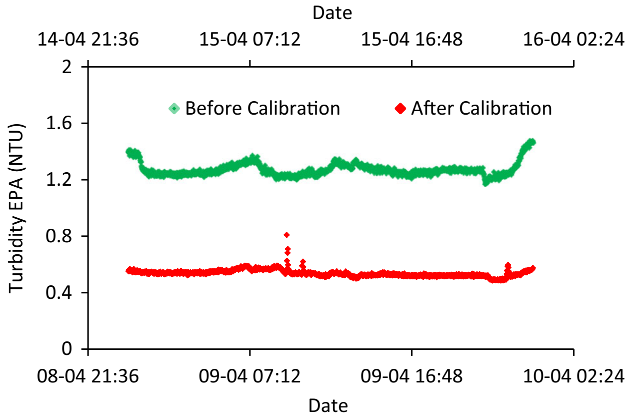

Fig. 10 Turbidity EPA before and after calibration at Polytech'Lille

turbidity EPA, at Polytech'Lille, is reduced from an average about 1.4 NTU to 0.6 NTU to fit with laboratory tests.

4.5 Comparison of data recorded at Polytech'Lille and Barrois Restaurant

Figure 11 illustrates S::CAN data for the period April, 11–30, 2017 at Polytech'Lille and Barrois. It indicates that turbidity and TOC are very similar at both locations, except some peak events. However, the conductivity is higher at Barrois. The comparison shows that certain water quality parameters could differ between 2 locations at the campus, because of the difference in pipes ages and quality in the campus. This indicates the necessity of installing sensors at different locations of the campus.

5 Conclusion

This paper presented the use of smart water quality devices (S::CAN and EventLab) in a large-scale experimentation for the real-time control of the water quality in water distribution systems. The experimentation was and is still being conducted at the Scientific campus of Lille University.

The experimentation showed the capacity of these devices to detect some abnormal events concerning water quality, which were correlated with an increase in the water flow.

A comparison between recorded data and laboratory analyses confirmed the good performance of S::CAN concerning some parameters and the necessity to operate some adjustments for the calibration of other parameters (TOC and conductivity). The experimentation showed also the necessity to conduct regular maintenance of these devices.

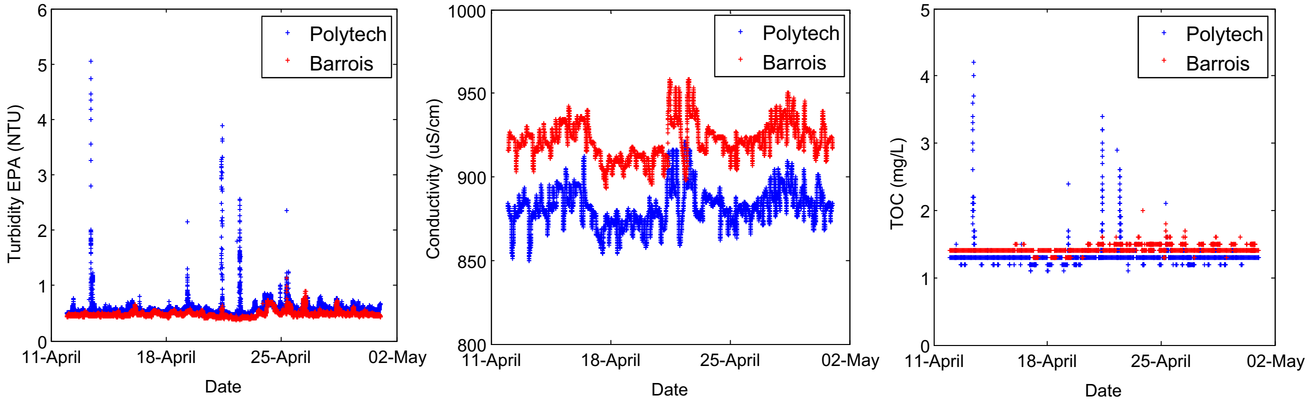

Fig. 11 Comparison of S::CAN data between Polytech'Lille and Barrois

References

1. Mounce, S. R., Gaffney, J. W., Boult, S., & Boxall, J. B. (2015). Automated data-driven approaches to evaluating and interpreting water quality time series data from water distribution systems. *Journal of Water Resources Planning and Management, 141*(11), 04015026.
2. Cooper, W. J. (2014). Responding to crisis: The West Virginia chemical spill. *Environmental Science and Technology, 48*(6), 3095.
3. Manual micro::station, s::can. (2011). *Intelligent. Optical.* Online. Technical description.
4. Micro::station. Monitoring stations. http://www.s-can.at/medialibrary/datasheets/microstation_dw_hp.pdf.
5. van Wijlen, M. A. B., Koerkamp, M. K., Xie, R. J., Puah, A. N., van Delft, W., & Bajema, B., et al. (2011). Innovative sensor technology for effective online water quality monitoring. In: *Proceedings of the 4th Singapore international water week*.
6. van den Broeke, J. The benefits of using refractive index for water quality monitoring in distribution network, A comparison of Optiqua EventLab and traditional water quality parameters, Optiqua, Published by *Optiqua Technologies*. http://www.optiqua.com/documents/20140804_OptiquaEventLabcomparison_withcover.pdf.
7. Tangena, B. H., Janssen, P. J. C. M., Tiesjema, G., Van den Brandhof, E. J., & Koerkamp, M. K., et al. (2011). A novel approach for early warning of drinking water contamination events. In *Proceedings of the 4th international conference on Water contamination emergencies: monitoring, understanding and acting* (Vol. 331, pp. 13–31). Cambridge: Royal Society of Chemistry.
8. Raich, J. (2013). Review of sensors to monitor water quality. *European reference network for critical infrastructure protection (ERNCIP) project.*
9. Optiqua. Refractive index as the new water quality monitoring standard. Mach Zehnder Interferometer. http://www.optiqua.com/mach_zehnder.html.
10. Building PI system assets and analytics with AF, OSIsoft, version 2016a.
11. Farah, E., Abdallah, A., & Shahrour, I. (2017). Sunrise: Large Scale demonstrator of the smart water system. *International Journal of Sustainable Development and Planning, 12*(1), 112–121. https://doi.org/10.2495/SDP-V12-N1-112-121.

Christine Saab received the Civil Engineering degree in 2014 from the Lebanese University, and a master degree in 2015 in collaboration between Lebanese University and the University of Lille. Since October 2015, she is a Ph.D. student between the laboratory of Civil Engineering and geo Environmental (LGCgE) in the University of Lille and the Doctoral school in Lebanese University. Her research consists the real-time monitoring of water quality using smart technology, especially water quality sensors.

Elias Farah received the M.Sc. degree in civil engineering from the Lebanese University, Faculty of Engineering, Branch 1, Tripoli, Lebanon and his Ph.D. degree from Lille University of Science and Technology, Lille, France. Currently, he is a lecturer at Lebanese University and Holy Spirit University of Kaslik (USEK), Lebanon. His research interests include leak detection in smart water networks and geo-environmental engineering.

Isam Shahrour is a distinguished professor at the University of Lille1 in France. Currently, he is director of the Civil and Geo-Environment Engineering Laboratory and coordinator of the SunRise Smart City project “A large scale demonstrator of the Smart City”. His research concerns soil-structure interaction, geo-environmental engineering and more recently Smart Cities. He published around 110 journal papers and supervised 70 Ph.D. theses. He was Vice President for “Research and Doctoral Program” at the University of Lille1 during the period 2017–2012.

Fadi Hage Chehade is a professor at the Lebanese University. He is the director of the Modeling Center, research laboratory, at the Doctoral School of Science and Technology. He is also the coordinator of a Master 2 in Civil Engineering with 3 options which is in double degree with the Lille I University-France. The main research activities are related to non linear numerical modeling of soil structure interaction problems and some environmental problems. He supervised around 15 Ph.D. and more than thirty M2 research topics.

Sana Ounaies is an assistant professor at the University of Lille in France. Member of the Civil and Geo-Environment Engineering Laboratory and working with the team of Sun-Rise Smart City project "A largescale demonstrator of the Smart City". Her main research area concerns Hydrogeology and more recently the water networks in Smart Cities.