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Practical guidelines on the requirements of a continuous online water-quality monitoring system in drinking-water-supply systems

ERNCIP Chemical and Biological (CB) Risks to Drinking Water Thematic Group

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Abstract

Recurrent incidents around the world involving the contamination of water-supply systems and the inherent vulnerability of drinking-water networks to chemical, biological and radio nucleotide contamination has increased water utilities' awareness of the need for rapid and reliable detection of contamination events.

Continuous water-quality monitoring is a proactive approach to monitoring water quality for potential contamination through the deployment of advanced technologies and enhanced surveillance to collect, integrate, analyse and communicate information, and is a fundamental element of the water-security plan.

This guidance document is aimed at professionals of drinking water supply to support the implementation of such a continuous water-quality monitoring system in water utilities. It provides key definitions and briefly explains each of the components of such a system. For each component, the guidance describes the major points to be considered by the water utility before and during implementation.

This document was prepared by the Chemical and Biological Risks to Drinking Water Thematic Group of the European Reference Network for Critical Infrastructure Protection (ERNCIP) (Gattinesi, 2018).

1. Introduction

Recurrent incidents around the world involving the contamination of water-supply systems, and the inherent vulnerability of drinking-water networks to chemical, biological and radio nucleotide (CBRN) contamination, have increased water utilities' awareness of the need for rapid and reliable detection of contamination events (Clark, Hakim and Ostfeld, 2011).

The proposal for a water-security plan has been developed by this Thematic Group. Complementary to water-safety plans, it addresses the risk of intentional or accidental contamination of drinking-water-distribution systems (Weingartner and Raich-Montiu, 2015; Hohenblum *et al.*, 2016). The main goal is to detect contamination incidents in time in order to reduce potential public-health and economic consequences.

The emergence of the internet of things, cloud computing and big-data analytics enable automatic remote collection of data from water-quality sensors located in the distribution system and wireless transmission to a central system for efficient and effective monitoring and analysis of the water network (Public Utilities Board Singapore, 2016).

Continuous water-quality monitoring (CWQM) is a proactive approach for monitoring water quality for potential contamination through the deployment of advanced technologies and enhanced surveillance to collect, integrate, analyse and communicate information, and is a fundamental element of the water-security plan (EPA, 2007, 2008).

The CWQM system is a suite of tools that constitutes a decision-support system (DSS), providing event managers with the information necessary to make good decisions, assisting in the evaluation of multiple response actions and thereby minimising further human exposure to contaminants and maximising the effectiveness of intervention strategies.

The CWQM system typically includes detailed geographic information system (GIS) mapping of the water network, a hydraulic model allowing calculations of flow directions and intensities in the water-piping system, water-quality sensors optimally located in the distribution system, an event-detection system (EDS) and a contamination dissemination model. A possible architecture of a CWQM system, which has been developed as part of the EU-funded FP7 Safewater project (Bernard, 2016; Safewater, 2016), is shown in Figure 1. Some of these modules have been state of the art for many years (e.g. hydraulic models), but others are relatively new and are only available as prototypes (e.g. advanced EDS systems; online simulators; and look-ahead simulators). It should be stressed that the integration of such a 'complete' DSS is currently quite a complex task, as there are no standards for the interfaces of the software modules.

The CWQM system is one component of the surveillance system which provides timely detection of water-quality incidents in the drinking-water-distribution systems. Additional components are physical and cybersecurity monitoring, customer complaints and public-health monitoring and laboratory analysis.

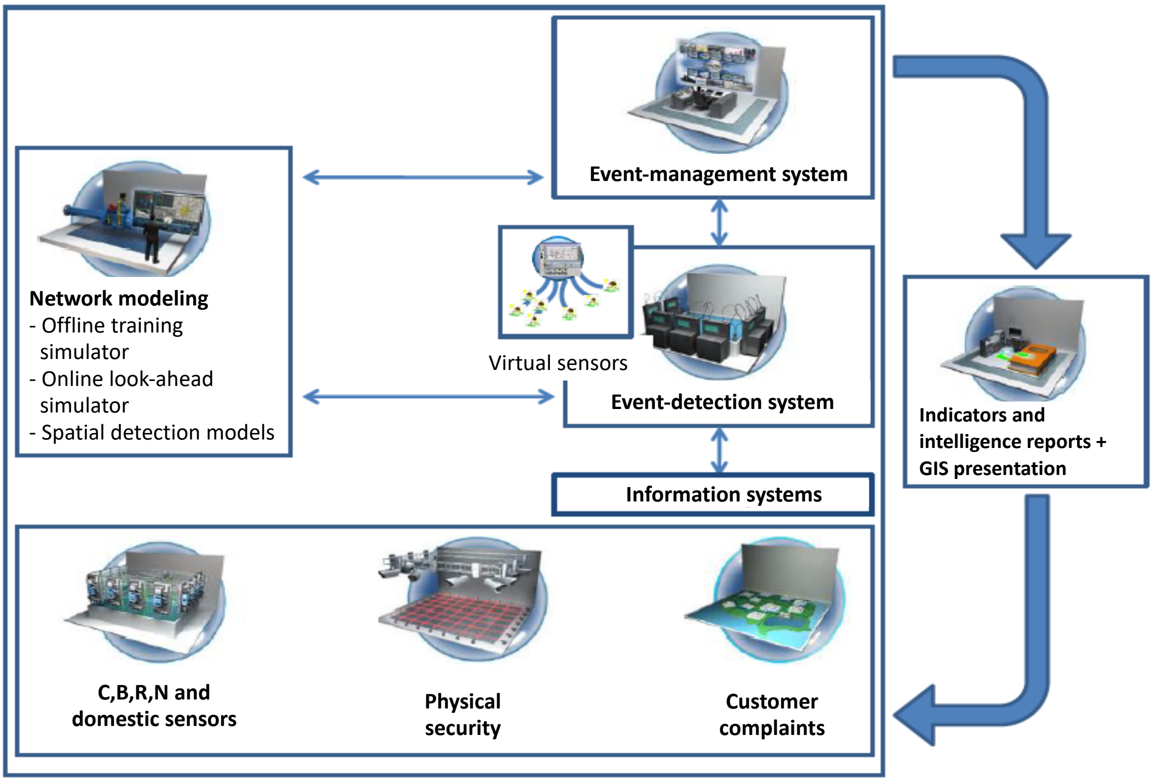
Once integrated into daily operations, the CWQM system will respond to deliberate acts of contamination such as terror or sabotage actions, as well as natural disasters, accidents and mishaps or operational mistakes. It can also be used to further understanding of the operation of the water-distribution system.

Drinking-water-distribution systems are large networks consisting of raw water sources, treatment plants, storage tanks, valves, pumps, instrumentation and hundreds to thousands of kilometres of pipes that transport treated water to customers over vast areas. The nature of the drinking-water-distribution systems and the high velocities and volumes of water in the networks can allow contamination to reach large populations in a relatively short time. The CWQM provides valuable insight into real-time and near-real-time conditions throughout the water-supply network, from the water source to the customer connection, thus enhancing protection from contamination.

The CWQM system is a vital management tool to monitor the water network and a DSS to detect anomalies. The CWQM system enables earlier event detection, thus giving time for actions to be carried out to minimise contaminant dissemination, limit the health impact on residents and restrict damage to the water network, thus enabling faster rehabilitation and effective mitigation of the economic impact (EPA, 2008).

The basis of a CWQM system is a network of water-quality-monitoring stations deployed at strategic locations throughout a drinking-water-distribution system. Each station contains a suite of sensors that measure water quality and operational parameters. Real-time and near-real-time water-quality data collected from sensors is continually analysed by the event-detection system (EDS) and allows the utility to rapidly detect water-quality anomalies (van der Gaag and Volz, 2008; EPA, 2015; ISO, 2018b).

Figure 1. Possible modules and architecture of a CWQM system



Source: FP7 Safewater project: http://safewater-project.eu

The design process of the CWQM system is a multi-objective task that requires informed decision-making, using optimisation tools and making various assumptions for different objectives. Water utilities must weigh the costs and benefits of various designs and understand the significant public-health and cost trade-offs.

Traditional chemical and biological analytical analyses (field sampling and analysis in the laboratory) have to be carried out to confirm and identify the nature of the contamination by recognised methods. The Thematic Group is preparing a report on such analytical methods to be released in 2019.

The installation, implementation and operation of the CWQM system requires the input of the utility's hydraulic engineers who are familiar with the water network, water-quality experts, electronics and communication experts, IT security experts and skilled technicians.

These guidelines briefly explain each of the CWQM components and include necessary definitions, so that users will be familiar with the professional terms that may arise during CWQM system implementation in the utility. For each component, we will describe the major points to be considered by the utility before and during implementation.

2. Hydraulic model and geographic information system application

2.1. General

The various components of the CWQM system, for example software for the optimal location of water-quality sensors in the water-distribution system, EDS, water quality and the contamination dissemination look-ahead simulation (CDLAS) model, require detailed information regarding the physical aspects of the water system and detailed water-demand information.

A hydraulic model is commonly used to analyse water utility networks, and is an indispensable tool for creating a master plan for the development of the system and capital improvement plans. The model can help utilities evaluate system performance under various operational scenarios and identify future improvements necessary for such parameters as meeting water-pressure requirements.

A hydraulic model is a mathematical representation of the water system which can then be used to examine the behaviour of the system. It calculates the pressure losses throughout the system (for a given water demand) and presents the pressures expected at each node (junction) in the pipe system. These calculated pressures can be compared to pressure requirements. The model operator can than posit improvements in the distribution system (for example increasing the diameter of certain pipes or regulating pumping pressure) in order to effect the desired changes in node pressure. Increased demand expected in the future can be run on the model, thus predicting which pipes will have to be upgraded in terms of diameter, what pumping capacity must be increased in order to provide future demand at the desired pressures or what water-storage capacity must be built by which year in order to provide 24/7 service.

In order to calculate pressure losses in the system, the model must first calculate the flow speed of the water in each and every pipe as well as the direction of the flow. This data is vital to understanding the flow characteristics of the system (which can change according to what hour of the day or what day of the week it is, or even according to the season, whether summer or winter) and thus the ability of the system to disseminate a contaminant introduced at a certain point in the system.

Flow data is clearly an important tool in modulating the water-demand characteristics of the hydraulic model, but use of pressure values measured by field sensors in the CWQM stations may further adjust the model. This makes the model’s representation of the system even more realistic and provides the CDLAS model user with a true reality-based prediction of the contamination-spread zone.

The hydraulic model can work in two configurations: ‘offline’ and ‘online’.

- The offline function for simulation using past data means that the water-demand data is taken from the stored database. This data represents a historical average water-demand profile, not modified to current conditions.
- The online function uses updated online data of the inflow and the water demands, and may include reservoir levels, pump operation, water-flow measurements, etc. The online approach provides more accurate and relevant results and thus a better prediction of the water flow through the system.

The location of water-quality sensors is dependent on the flow characteristics of the system, as calculated by the hydraulic model.

Utilities that obtain water from multiple sources can use the hydraulic model and GIS to calculate the proportional mix of the various water sources throughout the network. It is a good indication of overall customer water quality.

2.2. Implementation requirements

The hydraulic model is both expensive and time-consuming to create. Most medium-sized and large utilities may create a hydraulic model as part of their master plan. Several platforms for creating a hydraulic model exist and some are even free to download. The implementation requires experienced and knowledgeable engineers to apply the downloaded platform to a particular utility.

Creating the model requires detailed physical information on the water system (reservoirs, pumps, pipes — diameter, material, age, length, route), detailed data on water consumption for every consumer (estimates can be used, but these limit the accuracy of the resulting model) and detailed maps including elevations (digital terrain model) (Public Utilities Board Singapore, 2016). It is also vital that the model be enhanced to receive online operational information.

The utility should consider a user-friendly interface that includes several layers, such as a water-network map, quality simulation, predicted spread, sensor nodes, the node numbers, etc.

The utility should verify that the hydraulic behaviour matches actual system operations and validate the hydraulic model by means of pressure studies.

2.3. Geographic information system

As mentioned above, the building of hydraulic models of the water system requires considerable information regarding the distribution system, such as pipe information — diameter, material, length, age, route location; location of valves, water installation, consumer meters; characteristics of pumping stations; detailed urban maps (streets, buildings, elevations, etc.); and more.

This information is most efficiently maintained and displayed in a GIS, which integrates, stores, edits, shares and displays spatial geographic information (Ginther, 2007). It allows users to create interactive user queries, edit data in maps and present the results of all of these operations.

Water utilities have traditionally maintained detailed system maps. Keeping the information updated has always been a challenge. GIS computerised tools provide the utility with an efficient means to update and disseminate distribution-system information, and to map the distribution of consumer water use; this information is in turn easily exported to the hydraulic model to serve as a basis for creating the model.

The GIS tool is extremely powerful in that it allows development of queries such as 'Show all pipes larger than 10' with age exceeding 40 years' or 'Show which valves are to close in order to isolate a given segment of pipe, and which consumers will suffer a water outage as a result of the closure', etc. The more information that is included in the GIS, the more benefits can be realised.

A GIS representation of the system allows easy and immediate access to information for all authorised users. Selected information can also be made available to the public.

3. Sensor-placement optimisation software

3.1. General description, the need and the benefit

The locations of CWQM stations must be optimised in order to obtain an early detection time, minimise public exposure to contaminants, minimise the spatial extent of contamination and reduce economic consequences (Ostfeld *et al.*, 2008).

The placement and optimisation software is a comprehensive tool based on an updated and calibrated hydraulic model that facilitates the proper location of CWQM stations. The software uses probabilistic analysis and optimisation to conduct a vulnerability assessment and determine the optimal number and location of CWQM sensor stations in the distribution system.

CWQM station-placement strategies can be based on a computational model but should also consider expert opinion and/or user-preference information (proximity to critical facilities) to rank network locations.

The operation of the placement-optimisation software should be carried out by an appropriate expert, in conjunction with the utility's hydraulic engineers and water-quality persons, and should also include on-site feasibility assessments.

Several specialised computer tools are available for carrying out sensor-placement optimisation. These programs posit the introduction of a contaminant in any number of nodes in the distribution system and examine each scenario for selected results (e.g. total length of pipe contaminated until contaminant arrives at a sensor location). Too many sensors are an unnecessary expense; too few allow too much of the system to be 'unprotected'.

The number of monitoring stations is also calculated by the software. A 'knee of the curve' analysis is done — this indicates the number of stations above which there is only a small increase in the network percentage coverage, making the additional stations not cost-effective.

3.2. Implementation requirements

For an optimum number and location of CWQM stations in a drinking-water network, the utility must first decide on its optimisation policy (Preis, Whittle and Ostfeld, 2011; Thompson *et al.*, 2011). For example, is the policy to limit the number of people exposed in a contamination event? Or do we want to minimise time to detection? Do we wish to minimise the total pipe length contaminated? Do we wish to give precedence to and 'protect' certain vital consumers? The utility must also consider its 'time of reaction' in the total optimisation picture. Other considerations involve the efficacy of using average consumption data as opposed to maximum or minimum levels.

Objective functions relating to public-health impacts may be the highest priority and therefore may be chosen.

An optimal sensor placement is done with the assumption that all incidents are equally likely (uniform event probabilities because, typically, one does not have information about terrorist intentions), and is evaluated using a distribution of impact values for the entire large set of contamination incidents. However, the utility may decide that certain contamination scenarios are more likely than others. The mean value of an objective function is a natural statistic, while it can still allow many high-impact contamination incidents to occur.

All of the above considerations affect 'optimal' sensor placement. In the end, the optimised sensor-placement results increase the chances of early event detection and damage reduction.

The information that has to be collected and decided upon by the water utility before the optimisation process includes the layout of the water-distribution system and the operating information as expressed in the hydraulic model, the sensor characteristics, the type of event, the objective functions and the utility's response plan.

3.2.1. Hydraulic model data

The hydraulic model is the backbone of the sensor placement and optimisation software. A well-calibrated, extended-period simulation hydraulic model is important for accurate representation of system performance under average-day conditions, and for the ability to represent the spread of the contaminant throughout the distribution system. See also the hydraulic model chapter.

The following hydraulic model network characteristics are important for CWQM placement-optimisation simulations:

- network details of main and other pipes that are considered critical from a security point of view, junctions, treatment plan, reservoirs, pump stations, valves;
- pressure, flow, reservoir-level field data collected from the supervisory control and data acquisition (SCADA) system;
- water age — the travel times from the source to the customer nodes in the specific water system;
- common operating conditions throughout the year (e.g. relatively average conditions throughout the year);
- daily average water consumption during periods with different levels of demand, which influence flows and velocities (e.g. average high demand of a summer day, average low demand of a winter day, maximum demand in extreme cases such as fires);
- multiple water sources and water-mixing information;
- water quantity coverage;
- topography;
- areas with a higher risk of threat and protection, such as important and sensitive institutions (hospitals, military bases, government buildings, etc.);
- the size of population served;
- the population density (calculates population using either a demand-based approach (an average-per-capita demand, no differentiation for private or industrial and commercial usage) or a census-based approach (uses census data and a GIS) but does not account for the non-resident population).

3.2.2. Sensor characteristics

The water-quality sensors in CWQM stations have multiple parameters, modelled with contaminant-specific detection limits that reflect the ability to detect chemical contaminants (Wagner *et al.*, 2006).

The sensor characteristics are also important for CWQM placement-optimisation simulations:

- monitoring station location selection (all or limiting feasible nodes);
- sensor type;
- detection limit according to the disinfection method used in the water system;

- sensor accuracy;
- sampling programme.

For more details see Section 4.

3.2.3. Event types

If the utility has some information or an assumption regarding event types, as mentioned below, they are also important for CWQM placement-optimisation simulations:

- types of contamination threat such as high-impact incidents, low-impact incidents that might be caused by accidental backflow, or cross-connections;
- the simulation duration (to determine the average water age in the distribution system and the oldest water age under average-day demand conditions);
- the start time of the contamination incident (on the peak/average/lower demand time of the system);
- the duration of contamination and the mass released (for a low-impact contaminant, a larger mass is required if injected over a short duration and a smaller mass is required if injected for longer durations; and for a high-impact contaminant, less mass is required for a longer release duration);
- rate of contaminant injection (pipe-flow rates used to calculate mass-release rates for the selected low-impact and high-impact contaminant durations);
- contamination dissolved rate;
- dose calculation (depends on the contaminant concentration in the water and the amount of water consumed);
- injection locations of the contaminant may not be known— meaning the number of possible sources and the number of nodes to consider as a potential source of entry, resulting in the number of contamination incidents to check during the optimisation process;
- temporal pattern of water consumption.

3.2.4. Objective functions

The objective functions are among the most important parameters that can be selected by the utility for optimisation. It is important to understand the differences between the objectives when designing a CWQM station network. The software should have the ability to analyse and visualise the trade-offs between different objective designs, and between the number of sensors. The different objective functions are:

- time to detection;
- population exposed prior to detection;
- population exposed to a specified dose of contaminant;
- population affected by a contaminant;
- population killed by a contaminant;
- volume of contaminated water consumed prior to detection;
- extent of contamination in the network;
- damage to the water network;
- number of failed detections;

- the fraction of contamination incidents that are detected by the sensors;
- maximum spatial coverage of the network;
- protection of key facilities or populations.

Other objectives such as the costs of a CWQM or the economic impact on a water system could be considered as well.

Usually, the impact on public health that might result from a contamination incident is more important.

3.3. Utility emergency response plan

In parallel with installing a CWQM system, it is vital that the utility develop an emergency response plan, the aim of which is to eliminate or lessen further public exposure once a contaminant has been detected in the system. The plan should include all the immediate actions needed to respond quickly and reduce the damage. Response time is the total realistic time that it would take for the utility to respond effectively to a positive contamination detection, in order to eliminate or lessen further public exposure. The plan should aim at minimising response time.

Immediate actions could include effectively warning customers at risk not to drink the water, cutting off the water supply in the area at risk, stopping pumps, closing main valves, etc.

Minimising response time is important in the optimisation process described above because, as the response time increases, monitoring becomes less relevant even with a larger number of monitoring stations. It is of little use to invest heavily in a CWQM system if the utility does not know how to respond effectively to the alert the system has provided.

3.4. Optimisation software design

Optimisation software may use a single-objective analysis approach or may be capable of performing a multi-objective analysis (carrying out correlations between objectives).

The single-objective software allows the user to explore trade-offs between various CWQM station locations and choose the location design that performs well for more than one objective (EPA, 2010a).

The multi-objective approach is a computationally intensive process which analyses several objectives in parallel (Preis, Whittle and Ostfeld, 2011). It may optimise a weighted sum of different objectives or optimise one objective while constraining the remaining objectives. The utility should decide which objective function or functions to consider.

The software used must be capable of carrying out fast, exact and flexible calculations, dealing with large and complex water-distribution systems and handling the optimisation of large quantities of data.

The optimisation process may be based on different sensor-placement optimisers, such as integer programming solvers, genetic algorithms, local search and others.

Quality assurance is required in order to verify that all optimisation processes and simulations are running correctly and the utility can trust the results.

3.5. The optimisation process

3.5.1. The number of continuous water-quality monitoring stations

Before optimising CWQM station locations, the number of CWQM stations to be installed in the system must be determined. The optimal number of CWQM stations is determined using trade-off curves, such as 'knee-of-the-curve', in which additional monitoring stations beyond an optimal number (cost) provide only a negligible increase in network percentage coverage (benefit).

3.5.2. The location of continuous water-quality monitoring stations

The optimisation process integrates a great deal of data, including model assumptions and constraints, function objectives, sensor characteristics, etc., and presents the suggested optimal locations for CWQM stations accordingly (Philadelphia Water Department and CH2M HILL, 2013a; EPA, 2014b).

The monitoring station placement software determines the optimal monitoring station network for a specified contamination scenario. An optimal monitoring station set design is defined for a specific scenario, and this optimal design is then run within a different scenario for performance evaluation. The analysis conducted compares every optimal monitoring station set's performance across all design scenarios. This analysis makes it possible to determine the monitoring station set design that performs best in all cases.

The decision process begins by finding a sensor placement under ideal conditions and simplifying the assumptions. The assumptions are then removed one by one in order to make the results more realistic. At each iteration, the performance of the given sensor network design is compared quantitatively and visually with previous designs in order to understand what has been gained or lost with each assumption.

Based on the hydraulic model and on the objective functions decided upon, the optimisation software calculates the consequences of the set of contamination incidents that the monitoring stations is designed to detect. The software may consider contamination incidents that occur at every node in the network, minimising the mean value for a given objective — assuming that each contamination incident is equally likely — and therefore all are important to consider when selecting a CWQM network design. The software may also allow the user assigning a higher importance weight on locations with a higher likelihood of contamination.

Each solution needs some compromise. For example, using multi-objective analysis of the average volume of contaminated water consumed, detection time must be offset with detection failure: if the time-to-detection value is allowed to rise, this will result in fewer cases of detection failure. However, if minimum failure is demanded, this may result in a longer detection time.

The utility's estimated response time may also affect the placing of monitoring stations further upstream or downstream: if the response time is relatively high, it may be necessary to move monitoring stations further upstream in order to save at least part of the population from contact with contaminated water. Note that there could be a higher number of detection failures too. For an improvement in both reduced detection time and reduced detection failure, objective functions imply adding more monitoring stations to the solution. However, this has the consequence of increasing the costs, which could be a constraint for the implementation of the solution.

Various assumptions may be made during the analysis with the software expert that may influence the results of the analysis. For example, assuming a detection time equal to 48 hours for a given number of monitoring stations will lead to the location of the stations on the edge of the supply area and to the contamination of most of or the entire network. Assuming a detection time equal to zero will push locations upstream of the

previous location, thus allowing the utility enough response time to isolate and limit the dissemination of the contaminant.

Multi-objective analysis may consider all at the same time and without assigning weights, or in a different way.

3.5.2.1. Final location decision

Utility personnel must ultimately evaluate and compare optimisation results and decide on the final locations of the sensor stations. While CWQM location-selection software should be used to identify optimal CWQM locations, these sites may not always be practical. The possible influence of the site's characteristics on the sensor's operation and utility operators' experience and professional assumptions should also be considered. Therefore, several methods for identifying CWQM stations may be used.

The recommended location of the CWQM stations in various sites (e.g. reservoirs, treatment plants, pressure-reduction stations, metering points on network pipelines — pressure districts or district metering areas, etc.) should consider the possible influence of the site's characteristics on the sensor's correct and accurate measurements, and ensure appropriate and correct data transfer.

The site-specific requirements (if necessary) for the monitoring station are:

- sufficient environmentally protected secure space (appropriate temperature, humidity, free of condensation, vibrations);
- adequate source of pressurised and pressure-controlled water supply (use pressure regulator valves to avoid pressure and flow fluctuations that cause bubbles, high pressure);
- power supply and electrical backup;
- media for transmitting the data (wired or wireless) to a pre-specified data-collection location (avoid transmission interferences);
- drainage point for the sampled water;
- safety;
- clear access for installation and maintenance (water intake and drain lines below sensors, electrical noise suppression and transient impulse protection);
- influence on the false alarms detected by the EDS, which need a stable water-quality background with low pressure fluctuations;
- accessibility to the CWQM equipment at all times;
- security of the location.

Implementation of CWQM stations involves knowledge of the hydraulic model requirements, design basis, sensor-placement analysis, site selection and field verification.

4. The sensors

This section was compiled based on Hall et al., 2007; Panguluri et al., 2009; EPA, 2013a; Weingartner and Raich-Montiu, 2015; Geetha and Gouthami, 2016; Bazargan-Lari, 2018.

4.1. General

For the purpose of these practical guidelines the sensor term, which reflects practitioners' use, will be used. Nevertheless, other terms and definitions are mentioned in the table.

Table 1: Definitions of sensor-related terms (ISO, 2003; IEC, 2018; SABE, 2018)

Organisation	Term	Definition
IEC	**Sensor/ measuring element**	Part of a measuring instrument or measuring chain, which is directly affected by the measurand and which generates a signal related to the value of the measurand (IEC, 2018).
IEC	**(Electric) sensor**	Device which, when excited by a physical phenomenon, produces an electric signal characterising the physical phenomenon (IEC, 2018).
ISO	**Online sensor/ analysing equipment**	Automatic measurement device which continuously (or at a given frequency) gives an output signal proportional to the value of one or more determinants in a solution which it measures (ISO, 2003).
CEN/SABE ENV	**Sensor**	Electronic device that senses a physical condition or a chemical compound and delivers an electronic signal proportional to the observed characteristic (SABE, 2018).
CEN/SABE ENV	**Measuring device**	Device, used in an in-line or online operating position, which continuously (or at a given frequency) gives an output signal proportional to the value of one or more determinants in waters which it measures. The final measure is obtained from a sensor (SABE, 2018).

Sensors should be chosen not only to achieve water-security goals but also to accomplish other water-utility objectives, such as satisfying regulatory monitoring requirements or collecting information to solve water-quality problems. Such an objective would be particularly interesting and likely to be highly correlated with security objectives.

Continuous monitoring sensors can be used to detect anomalous changes in water quality, but further action (e.g. grab sample and laboratory analysis) must be undertaken to identify and quantify the contaminant. A laboratory support system will be important if samples require specialty testing as hazardous substances or a law-enforcement response, or overflow analysis. The Thematic Group is preparing a report on such analytical methods to be released in 2019.

4.2. Type and number of sensors

The type and number of sensors in the monitoring station should be determined according to the results of a risk analysis that should be carried out for each of the proposed stations. The most appropriate sensors together with an appropriate

combination of sensors specific to an individual drinking-water network should be decided upon.

Sensors' functionality and capabilities should be assessed (singly and in combination) for their relevance to the water utility's drinking-water network in general and their proposed installation locations in particular.

It is not feasible to install an unlimited number and unlimited types of sensors in each monitoring station. The utility should undertake careful planning to create the most effective, efficient and economically suitable monitoring system. Some water-quality parameters respond to a larger number of contaminants than others.

For CWQM there are different types of sensors. This sensor can be used in different ways depending on its operating position:

Online sensors: in which the sample is taken from the body of water to the sensor by means of an appropriate conduit. They are sometimes referred to as extractive sensors.
In-line sensors: in which the sensor, as a minimum, is situated in the body of water.

Each type has advantages and disadvantages.

There are many different monitoring devices based on different types of sensors that measure voltage, intensity or absorbance, among other things. In some cases the sensor can measure the signal directly but in other cases the use of reagents or pre-treatment of the sample is required to allow the measured compound or property to be detected by the sensor.

The utility should consider choosing the different types of sensors according to their suitability to the requirements, cost, maintenance and market availability for each water-quality parameter.

The state of available sensor technologies and changing contaminant monitoring trends and priorities should be followed and evaluated by the utility to assess whether changes should be made to their CWQM stations.

4.2.1. Low-energy online sensors

Recently available stand-alone low-energy (LE) sensors, which check several water-quality parameters and are based on batteries, solar cells or hydraulic power, allow for first-time water-quality monitoring within the water-distribution network itself, where there is usually no electricity supply available.

LE sensor installation in the water-distribution network requires preparation such as excavation and pipe work, including valve installation, to create a platform on which to install the LE sensors.

LE sensors are based on data transfer at determined time intervals (to save energy), but must be capable of transferring data in real time when an event occurs.

Networking of specific sensors in CWQM stations makes it possible to create a spatial model in the EDS for better protection.

4.3. Requirements

Online water-quality sensor alarms are a reliable indicator of a contamination event. Stable or predictable baseline water-quality levels are needed for each location. Background-value variations need to be considered when locating online sensors and interpreting data.

The sensors chosen need to satisfy the accuracy and precision requirements of the data-quality objectives. The utility should consider, among other things: stated range(s), response time, limit of detection, limit of quantification, repeatability and reproducibility.

The utility should consider sensor performance in terms of:

- type of contaminants considered to be a threat;
- environmental-condition requirements for proper operation of the sensor;
- capital and installation costs;
- operating costs such as consumables, reagents and labour costs (initial implementation and shake-down period — complex sensors require a high level of technical skills);
- maintenance requirements (for year-round operation, maintaining a tight maintenance schedule is necessary to obtain optimal sensor performance);
- the frequency of calibration;
- the ability to generate reproducible data at various contaminant-concentration levels;
- failure rates (both false positive (FP) and false negative (FN) rates need to be considered);
- data acquisition and interpretation specifics;
- data communication and transfer;
- verification testing as well as laboratory resources for confirmation of results;
- safety and waste issues.

Once the sensors have been selected they should be installed in accordance with the instructions provided by the manufacturer to meet flow, pressure and sample conditioning requirements. Specific installation requirements such as distance from the water being measured, type of connection, waterline installation angle and the need for accessories such as pressure regulators and water-bubble valves should be carefully fulfilled to ensure proper measurements.

Pressure fluctuations, flow control and air-bubble formation might negatively influence the data quality of many continuous-monitoring sensors. Manufacturers should provide robust non-fouling flow controls in their equipment to eliminate the potential for air-bubble formation in the sensor. Some of the monitoring stations to be found on the market do already include this concept in their design.

The sensors should include alarm outputs to identify instrument-related problems such as low reagents, instrument calibration drifts, etc. That is a part of the software of the monitoring station that is highly relevant.

The design and structure of different water-quality parameter sensors are not included in this document (EPA, 2013a).

4.4. Operation, maintenance and calibration

In order to obtain reliable and accurate information from CWQM stations, it is vital that maintenance and calibration be carried out on the system. This includes preventive maintenance of the sensors, periodic verification, calibration, troubleshooting and thorough record-keeping. Periodic comparison of measuring-device measurements with field portable meters and/or laboratory measurements helps to ensure that the data values are an accurate representation of the actual water quality. Erroneous results can result in false alerts or missed events.

Before purchasing sensors, the utility should consider the frequency of calibration and maintenance, and the possibility and cost of carrying out calibration by remote control.

To ensure proper operation of the sensor, environmental conditions, as per the manufacturer’s instructions, must be met.

Skilled personnel should supervise sensor operation and respond promptly to alarm flagging.

The water utility should establish a preventive maintenance programme with a frequency determined by the manufacturer’s instructions and modified according to the utility’s

experience. It is advisable to identify all the elements (pipe cleaning, reagents, biofilms, etc.) in the measurement chain that can affect the productive cycle (time between maintenance) and reliability of the result, and include them in the preventive maintenance programme to be verified.

Ideally, the utility should provide their personnel with internal training on the operation and maintenance of the CWQM stations.

Where this is not possible, the utility may consider contracting out the maintenance work. In any case, maintenance and repairs should be carried out only by skilled personnel.

A stock of spare parts, standards and reagents should be kept as needed for routine operation, maintenance and calibration. Care should be taken not to exceed the shelf life of items such as short-life reagents.

The equipment documents, CWQM station design drawings and the maintenance and calibration records of each sensor and component of the CWQM station should be documented.

The water utility should ensure that the relevant supply chains have the necessary time-of-delivery resilience to deal with equipment malfunctions.

4.4.1. Calibration

Calibration of the sensors should be carried out by a qualified utility employee in accordance with the manufacturer's or supplier's instructions and at the intervals required by the manufacturer or the supplier and/or the water utility's sensor-calibration policy.

The calibration can use portable field-measuring instruments, standards, reagents and accessories as reference, or may need a qualified laboratory as reference.

Standard operating procedures (SOPs) for operation, calibration and maintenance should be developed and used.

4.5. Parameters

Currently, no single water-quality parameter, or combination of parameters, can respond to all contaminants and can accurately identify and quantify the many different types of chemical and biological contaminants that could potentially be introduced into the drinking-water-supply/distribution system. No single parameter can give an indication of the potential toxicity of complex mixtures. Therefore, a combination of specific and generic parameters is advised.

Therefore, the parameters to be measured should be decided upon on a case-by-case basis for each water utility and deployment site. Utilities should consider installing more than one type of sensor in each of the CWQM stations.

The parameters monitored online or in line should correspond to the kind of water found at the monitored site: raw surface or ground water, water stored in reservoirs, processed water in a treatment plant, final treated water in the distribution network — reservoirs and pipes.

Whether the water is chlorinated, chloraminated or unchlorinated should also be taken into account when selecting the parameters and sensors.

The parameters monitored in distribution systems determine both types of water-quality incidents (intentional or unintentional contamination event) that can be detected by CWQM and the multiple benefits of improved water quality closer to the point of use.

4.6. Common parameters

Some water-quality sensors respond to a larger number of contaminants than others.

Below is a description of some common water-quality parameters to be measured by sensors, currently in use, that can be installed in the CWQM station to detect contamination. Other measurement parameters and sensors can be used to fit the utility's monitoring needs and capabilities.

4.6.1. Chlorine

Chlorine sensors measure free chlorine, monochloramine and total chlorine.

Chlorine is a powerful oxidising agent used widely in water-supply systems for disinfection. Chlorine responds to a large number of contaminants and reacts with many of the organic compounds and some of the inorganic compounds in water. These chemical reactions consume active chlorine from the water ('chlorine demand'), causing a drop in the measured value proportionate to the concentration of the chemicals that have been oxidised.

Chlorine decline or a drop below a threshold value may be a reason for an alert, based on field and laboratory experience.

A free chlorine residual parameter is a sensitive indicator for several contaminant classes such as pesticides, inorganic compounds, chemical-warfare agents, pathogens and bacterial toxins. In chloramine water systems, which were found to be stable in the presence of those contaminants, it does not appear to provide a reliable means of contaminant detection.

In those water systems where chlorine is not introduced into the water for disinfection, there is no point in using this type of sensor.

4.6.2. Turbidity

Turbidity is a measure of cloudiness of the water and is caused by suspended particles (matter or microorganisms). Pathogens are more likely to be present in highly turbid waters.

Turbidity sensors measure suspended solids in water, typically by measuring the amount of light transmitted through the water. Turbidity may be useful in understanding observed changes in other parameters.

An increase in the concentration of suspended contaminants in the water will cause an increase in water turbidity. The above increase, or the crossing of a maximum threshold value, is a reliable indicator that the water quality has changed and an alert should be raised.

4.6.3. pH

The pH value is a measure of the activity of hydrogen ions in the water, therefore it is a measure of the degree of acidity or alkalinity of the water. Most chemical and biochemical processes are pH dependent. A change of more than 0.5 pH units indicates a problem.

The pH is a logarithmic scale, and its change also depends on the water-buffer capacity. It therefore requires a large amount of chemical contaminant to cause significant changes in the sensor readings.

pH may be useful in understanding observed changes in other parameters, such as free chlorine.

Changes in pH-level readings of the sensor above or below determined threshold values can be used as an input signal for alert determination.

4.6.4. Conductivity

Dissolved mineral substances in the water are directly related to the total ionic concentration and electrical charge of the dissolved matter, and can be measured as conductivity. A high volume of contaminants is needed to change the sensor readings significantly.

The conductivity parameter is an indicator for several contaminant classes such as inorganic compounds, metals and radionuclides. Many organic materials do not exhibit a net electrical charge and hence are not detectable through changes in bulk conductivity.

Electrical conductivity changes above or below determined threshold values may be used to raise an alert signal.

4.6.5. Total organic carbon

Total organic carbon (TOC) reflects the amount of organic carbon-containing compounds.

TOC sensors are successful in detecting many hazardous organic chemicals and biological contaminants such as petroleum products, pesticides, chemical warfare agents, pathogens, bacterial toxins, plant toxins and persistent chlorinated organic compounds. TOC may be correlated to chemical and biological oxygen demand.

A rise in the TOC values in the water above a threshold value can be used as an input signal for alert determination.

4.6.6. Oxidation-reduction potential

The oxidation-reduction potential (ORP) is the tendency of the water to oxidise or reduce another chemical substance.

ORP sensors measure the ORP of the water. Used in tandem with a pH sensor, the ORP measurement provides an insight into the level of oxidation/reduction reactions occurring in the water.

Some chemical contaminants can affect and change the redox-potential readings produced by the sensor.

ORP behaves similarly to residual chlorine and can be used to corroborate an observed change in the residual chlorine. ORP may be used in systems that use chloramine disinfectant.

Significant changes in the readings above or below determined threshold values may be used to raise an alert signal.

4.6.7. Particle counter

These sensors count the number and size distribution of suspended particles in water.

An increase in the readings of particle-count values in comparison to a specific water-pattern background may raise an alert.

The particle size ranges may be related to biological organisms. Particle-count measurements may be related to turbidity measurements.

4.6.8. Ultraviolet absorption

The ultraviolet (UV) 254 nanometre wavelength (UV254) absorption sensor can measure organic compounds that absorb photons at 254 nm. It is indicative of organic compounds with an aromatic chemical structure and conjugation. However, monitoring of the UV spectrum provides much more information from organic compounds. Monitoring of the UV spectrum, as recommended by EPA, even makes it possible to detect deviations from ‘typical’ water quality by detecting unusual peaks of absorbance in the UV spectrum.

4.6.9. Ultraviolet-visible spectroscopy

Ultraviolet-visible spectroscopy optical spectrometer probes allow the monitoring of many different parameters such as nitrates, total organic carbon, colour, turbidity, UV254, temperature, etc. in one single measuring device. Since it is optical, it does not require reagents or consumables.

4.6.10. Dissolved oxygen

A concentration of oxygen dissolved in water can serve as an indicator of chemical and biochemical activity in water.

4.6.11. Temperature

A measurement of how hot or cold the water is. Biological and chemical activities are heavily influenced by water temperature. Dissolved oxygen and specific conductance change with temperature.

4.6.12. Microbiological parameters

The availability of the microbiological online or in-line sensors is limited.

There are several bacteriological sensors for *E. coli*, coliforms, and total bacterial count. As the required detection time can be longer than for other parameters, the suitability of its measure can be indicated more for the control of the processes.

4.6.13. Refractive index

The refractive index (RI) is based on the property that describes how light propagates through water. A known matrix of dissolved compounds has a specific RI; when different compounds are dissolved in this matrix the RI can change.

4.6.14. Other online sensors

There are more water-quality parameter sensors for specific and general purposes, for example toxicity bioassay sensors based on the behaviour changes of various kinds of living water organisms due to chemical contaminants in the water, or for individual chemical contaminants, which are not reviewed here and which may be found in the literature.

4.6.15. Operational parameters

Continuous measurement of operational water parameters such as flow, pressure, reservoir tank level, etc. can improve the water utility’s interpretation capabilities with regard to water quality and should also be considered for installation, according to the hydraulic characteristics of the water network.

4.7. Data communication and transfer

4.7.1. General

The large amount of data produced by the sensors in all CWQM stations has to be collected, stored and analysed in order to detect water anomalies and give an alert. Some of the existing CWQM systems already include software running on the local terminal in order to validate the data before it is sent to the SCADA system, and even local software to detect events due to changes in water quality.

SCADA systems, central EDS or local single-board computer devices in each CWQM station are needed to fully utilise and process, in real time, the large volume of data generated by the sensors.

Backup of the data in the SCADA and/or the EDS is needed. Ideally, the measuring devices should include local data loggers.

The sensors can be interfaced with a variety of SCADA and EDS systems using various kinds of communication methods and protocols. The communication should be universal and allow for different communications systems to interface and connect to the central servers and be based on protocols that are standardised and secured.

The data transferred from the sensors to the SCADA or EDS systems should be considered critical information, and the transfer and handling of the data should be carried out according to cybersecurity recommendations and IT security requirements. Wireless data transmission should use secure protocols, data encryption, firewalls and other robust technologies that reduce the attack on data transmitted from field-deployed monitoring sensors to the central servers.

The utility should ensure an uninterrupted power supply for the operation of measuring devices and for data transfer. The utility should be assisted by professionals regarding the requirements for secure communication and data transfer between the sensors and SCADA or EDS systems.

4.7.2. Communication methods and protocols

The transmission of the data from the sensors to the SCADA or EDS systems may include digital lines, cellular networks and radio wireless networks.

The type and quantity of the data, the locations of the CWQM and the existing communication capabilities will impact the selection of the methods that will be used. Each communication method has different kinds of communication protocols for transmission and reception.

Communication of data is a major source of power consumption, especially in LE sensors installed along the water network with no power-supply infrastructure.

The stages of communication are as follows.

The sensor converts the primary signal measured into an equivalent measurable electrical quantity, and after its amplification and processing obtains the value of the desired parameter which is given as an input to controllers through wired or wireless communication devices.

The controller gathers the data from the sensors, optionally processes it and sends the information to the SCADA/EDS by using an appropriate means of communication technology.

The SCADA/EDS accesses the data-storage base or cloud, manages and analyses the data, displays the information and alerts the user.

The physical layer includes the hardware, communications lines and wireless components such as Wi-Fi, Bluetooth, GSM/GPRS, ethernet local area networks (LAN), etc.

The logical layer includes protocols — which define the message structure, the encryption, the decoding, etc. — such as Modbus, Profibus DP, ZigBee, TCP/IP, LoRaWAN, etc. The protocols may work with wired or wireless hardware.

Different communication technologies and protocols are used for information transfer between the sensor, the controller and the SCADA/EDS systems. Some protocols are applicable between the sensor and the controller, and some between the controller and the computer, such as SCADA or EDS.

4.7.2.1. The hardware

- Wi-Fi is a technology for wireless local area networking (WLAN) that transfers data between devices within a limited area, based on radio waves.

- Bluetooth is a wireless technology standard for exchanging data over short distances, based on radio waves.
- GSM/GPRS (General Packet Radio Service) is a packet-oriented mobile data service on the second- and third-generation cellular communication system's Global System for Mobile communications (GSM — standard developed to describe the protocols for second-generation digital cellular networks used by mobile devices). It requires the addition of a SIM card to the sensor station.
- Ethernet LAN is a family of computer-networking technologies commonly used in LANs. Systems communicating over ethernet divide a stream of data into shorter pieces called frames (digital data transmission units).

4.7.2.2. The protocols

- Modbus is a simple free communication protocol, easy to deploy and maintain, for connecting electronic devices. It is also used to connect a supervisory computer with the remote terminal unit (a microprocessor-controlled electronic device that interfaces objects in the physical world with a SCADA system by transmitting telemetry data to a master system, and by using messages from the master supervisory system to control connected objects).
- Profibus DP (Process field bus Decentralised Peripherals) is used to operate sensors via a centralised controller.
- ZigBee is a communication protocol used to create a personal area (close proximity) network (a digital telecommunications network used for data transmission among devices) with small, low-power digital radios. The technology is intended to be simpler and less expensive than other wireless personal area networks such as Bluetooth or Wi-Fi. ZigBee is typically used in low-data-rate applications that require a long battery life and secure networking, and is best suited for intermittent data transmissions from a sensor.
- TCP/IP (transmission control protocol and internet protocol) is a set of communications protocols used on the internet and similar computer networks. It provides end-to-end data communication, specifying how data should be packetised, addressed, transmitted, routed and received.
- LoRaWAN is a low-power wide area network specification intended for long-range communications among wireless battery-operated sensors. LoRaWAN targets the key requirements of the internet of things such as secure bi-directional communication, mobility and localisation services. The LoRaWAN specification provides seamless interoperability among smart things without the need for complex local installations.
- Communication between different controllers and computers is supported by open platform communications, a series of standards and specifications for industrial telecommunication. It allows continuous real-time data, between different controllers of different vendors and the SCADA/EDS systems, to be easily and securely integrated, and can also deal with events and alarms without costly, time-consuming software development.
- The data should be stored in databases with open database connectivity and routinely backed up. Open database connectivity is a set of clearly defined methods of communication between the database and the data-analysis tools/applications such as SCADA/EDS to interface with the data in real time.

4.8. Quality assurance

In order to ensure the reliability of the data generated by the sensors, quality-assurance and -control systems need to be implemented to test sensor-performance levels prior to installation and during the service period. Some of the existing CWQM systems already include software running on the local terminal in order to validate the data before it is sent to the SCADA system.

Ensuring data reliability in the long term is a critical issue for CWQM sensors. It is vital to guarantee a low level of false events; otherwise the event manager cannot base their decision on the water-quality monitoring system.

Documentation and records of calibrations and maintenance activities of the sensors should be maintained and taken into account during the analysis of the data by the EDS. Ideally, CWQM systems should provide a notification when sensors need maintenance.

The utility technicians in charge of sensor maintenance and data transfer need guidance and a training programme.

5. Event-detection system

This section was based on Drinking Water Inspectorate, 2009; EPA, 2010b, 2013a, 2013b, 2014a, 2016; ISO, 2018a .

5.1. General — the need and the benefits

Water-distribution networks deliver drinking water to consumers through a system of pipes, valves, pumps, reservoirs and tanks. These networks are vulnerable to accidental or intentional contamination.

Detecting contamination in distribution networks is difficult because of the spatial extent of the systems, rapid flow rates and natural variability in water quality. In addition, distribution systems are looped, resulting in mixing, dilution and the spread of contaminants. The water utilities require a system that can rapidly identify the presence of contamination in the distribution network and provide support for decisions, in order to minimise public-health and economic impacts and to restore service to customers as quickly as possible.

The normal variability of water quality in the distribution system, coupled with the large amount of data emanating from the sensors, makes it a challenge to successfully detect transient contamination incidents. It is not enough to utilise set points (thresholds) in order to raise alarms. The EDS is a DSS software that has the ability to learn the water-quality characteristics of the system being monitored; to detect water-quality events (whether caused by foreign agents, unidentified contamination or operational events); and to log information and alert users to water-quality deviations and recurring events. The EDS helps the water utility throughout the continuum of a water-contamination incident to rapidly detect and interpret changes in water quality.

The EDS is a smart, analytical software for data analysis based on machine learning that contains statistical and mathematical algorithms to rapidly detect anomalous conditions in water-quality measurements. In spite of the fact that water-network parameters vary considerably over time due to normal changes in the operation of tanks, pumps and valves, and daily and seasonal changes in the source and finished water quality, as well as fluctuations in demand, the EDS is able to interpret the data and use it to detect anomalies (Brill and Brill, 2016).

The EDS detects an event by performing near-real-time analysis of the data and then assesses the probability of a water-quality event occurring at the current time step, taking into account the uncertainties as well as the known inputs relating to the quality controls.

The EDS provides early notification of events so that effective response actions can be implemented.

5.2. Advantages of using the event-detection system

- Minimisation of false alarms due to changes in water-quality parameters caused by operational processes or maintenance procedures.
- Detection of events characterised by something other than a threshold violation, such as anomalous leaps that do not violate the low/high user limits; auto self-learning of statistical borders; and detection of long-term patterns before these become critical.
- Violation of engineering rules set by the user.
- Detection of low-quality data (static parameter, unlikely time period, fixed noise) caused by communication interference of data transmission.

- Detection of un-ordinary behaviour of the input/output cards (electricity fault in the card or power supply).
- Detection of an abnormal event combination (known as 'similarity').
- Detection of event combinations previously defined as dangerous and calculation of their approximate time of occurrence.
- Ability to operate and detect unexplained variance between different monitoring stations with a spatial model (if included) based on sensor networking.
- Upgrading of the knowledge of professional workers and deepening of their understanding of water quality in the network.

5.3. The event-detection system software

When purchasing EDS software users should consider its performance (specificity, sensitivity), available support, the user-friendliness of the interface, compatibility with existing data-management systems, the ability to modify or add parameters, and cost.

The EDS can be located on a central server and acquire water-quality data from the SCADA system, or it may be installed on a local single-board computer device in the CWQM station, or as part of the sensor hardware.

Available EDS systems vary in complexity and have different logical units and variables.

Some EDS software, available on the market, is sensor-agnostic, i.e. it can analyse data from any sensor manufacturer for any type of water measurement and any number of sensors and monitoring stations, while some EDS systems work only with specific sensors.

Some systems are offline, analysing historical data, and some are online, analysing real-time data, while other systems can do both; some systems are more user-friendly and require less support; some systems work with a single parameter, while others work with multiple parameters.

The software includes various user interfaces through which users can view and manipulate the information such as different charts (line graph, histogram, 2D/3D density maps), specific tables with information regarding the water-quality raw data, the smart algorithm values and analysis, a GIS-based map showing all the monitoring stations, the list of the sites with current and historical events, the water-quality and operational-parameter values and rules, and different analysis reports. Users can navigate within the interfaces to get more details.

An EDS may include a spatial model which enhances the sensitivity of field sensors, thus improving their capability to detect water-quality anomalies while producing fewer FP alerts and fewer FNs (missed alerts).

5.4. EDS methods and algorithms

Different EDS systems are based on different approaches and various statistical algorithms. The algorithms in the EDS are designed to continuously learn the characteristics of the background water-quality signal. The algorithmic approach allows the recognition of changes in water quality due to hydraulic operations.

There are several EDS methodologies for detecting abnormal events, as follows.

- **Clustering.** This is an algorithm which groups vectors into several similar groups, where the members of each group are as similar as possible and the differences between groups are as large as possible. Clustering may be based on distance or density algorithms.

Examples of algorithms used in this method are: multivariate nearest neighbour (at each time frame the average distance to the nearest group of samples is measured).

Local density (counts the number of historical samples located in a cell, which is a logical region of data that compiles with a Boolean rule — OR/AND/NOT logical relationships).

- **Prediction.** One of the variables in a multidimensional space is considered to be a dependent variable, the value or class of which is related to the other variables. If the predicted value is too far from the actual value of the dependent variable or has a different class value from the actual value of the dependent variable, the new incoming record is considered abnormal.

  An example of an algorithm used in this method is: nonlinear or linear numerical prediction (the algorithms provide a means to automatically detect changes in water-quality sensor measurements by comparing the current measurements with their predicted values based on their historical data).

- **Noise pattern 1.** This examines the noise-pattern changes generated by multidimensional data. It uses the radial basis function to identify abnormal patterns in a moving window. The classification is true or false.

- **Noise pattern 2.** This is based on detection and classification changes in noise patterns. Noise is measured based on the distance travelled by an artificial particle located at the normalised coordinates of the multidimensional vector. The classification is also true or false but adds the hazard and non-hazard classification.

  An example of an algorithm used in this method is: dynamic noise (uses the imaginary centre of gravity of the water-quality measurements in order to measure the noise of the process captured as a travelling distance. The resulting curve has a maximum value due to the nature of the process. This threshold is violated when abnormal events occur).

  Other examples are similarity (to what extent the specific event combination is rare), distance (how far the specific event combination is from a known combination), topology (to what extent the specific event combination is a good/bad combination).

5.5. EDS communication

Monitoring data may be transmitted by means of the SCADA system, a third-party server or directly to the EDS.

Direct connection to the SCADA requires software-connection elements, knowing the database storage and its format, the names of the SCADA tags (of the sensors) that are to be monitored at each station, timing the data process in the SCADA and in the EDS and minimising data-transfer problems.

The utility may limit or rule out communication by non-SCADA means because of data-security issues. If interfaces between systems are implemented, they must pass security check.

The connection between the sensors, the central receiving station and the database may be through phone or ethernet lines or radio communications.

Each different EDS may operate the sensor data, SCADA, etc. through different kinds of text files (XML, CSV), but it is recommended that the whole system work on the same configuration file (see also the chapter on sensors).

The utility should seek the assistance of professionals regarding the requirements for secure communication and data transfer. Data transfers are considered to be critical information and should be carried out according to cybersecurity recommendations and IT security requirements. Wireless data transmission should use technologies for secure protocols, data encryption, firewalls and other robust technologies.

5.6. EDS installation and implementation

The installation, implementation and operation of the EDS may be divided into five stages: installation, learning, adoption, operating and running.

5.6.1. First stage — installation

The first stage is the installation of the EDS software and connecting all CWQM stations, SCADA and other data-management software to the EDS.

The utility may consider connecting the EDS to interact with other platforms and incorporate operational data, a hydraulic model, operations-data software such as enterprise resource planning software (maintenance activities and repairs, additional operations data on flow, pressure) and manual laboratory results (addition and confirmation data).

Utilities should ensure that the sensor stations and communication pathways are operating properly before installing and running the EDS system.

The employees responsible for dealing with the EDS should also be involved in the installation process, along with hydraulic and electronics engineers and IT experts.

For installation and operation of the EDS software, the utility should supply basic information about the water network, consisting of the following.

- The correct communication forms and protocols. The data input for the EDS during the implementation and operation process is usually generated or collected by other software systems. This data needs to fit the EDS so that the predictions will be at an acceptable level of uncertainty.
- GIS data of the distribution system, including CWQM station location, from the hydraulic model.
- The SCADA tags of all the necessary water-quality and operational parameters.

5.6.2. Second stage — learning how to use the software

The second stage is to familiarise utility personnel with the EDS software, including screens and tools, learning how to operate the software, input and change parameters, produce reports, etc.

A training programme and a detailed user manual should be provided by the EDS supplier.

The process of EDS software operation, maintenance, interpretation and classification by the utility should include skilled trained employees and procedures.

All authorised EDS users dealing with the EDS should have a training plan. It is important that they develop their skills and knowledge and enhance their experience. They should also take part in the implementation of the EDS.

5.6.2.1. Trained authorised EDS operator rules

- Input data needed for implementation.
- Access historical data and analyse it.
- Contribute to improving the EDS software.

- Amend the EDS as needed, taking into account the lessons learned.
- Run simulations.
- Write utility-specific reports that can be introduced into the EDS software by the expert.
- Test the security aspects of the EDS.
- Implement and check new versions of the EDS including the EDS smart indicators.
- Perform checks and maintenance on the EDS and develop procedures.
- Act as the intermediary between the different professionals, such as hydraulic engineers, electronics engineers, IT and computer experts, and the EDS expert.
- Be responsible for the utility technicians that maintain the CWQM station sensors.
- Be responsible, together with the EDS expert, for training the utility's EDS users.
- Be responsible for developing procedures on how the classification process should be performed and all the documentation needed, including the classification table and preparing the classification library.
- Be responsible for the EDS and act as the contact person for the EDS supplier.

5.6.2.2. Certified trained user rules

- Know how to operate the EDS.
- Be able to perform their roles during daily working hours as well as in a crisis.
- Know how to analyse the data, finding the causes of true and false alarms (e.g. pump and valve operation or maintenance) and classify events according to the procedures.
- If necessary, be aware of event escalation and response procedures.

5.6.3. Third stage — adoption of the software by the utility

The third stage is to determine the value of all water-quality and operation parameters and variables of the EDS.

For operation of the EDS software, the utility should supply values for the different variables and parameters of the EDS, as follows.

- The values of the quality and operational parameters such as the measurement range, limit values, the alert thresholds.
- The preferred time frame in which events should be detected, triggered and classified (can influence the number of FP events).
- A table showing event classification — how events will be classified in accordance with the cause.
- The severity and order of priority in which events should be handled.
- The accepted number of FP and FN events, specific to location and type, over a defined period of time.
- Adjust, if possible, the various EDS tables and charts to the utility's needs.
- Appoint authorised users, workers to receive alarm notifications, etc. according to the utility's needs.

The ability of the EDS to detect water-quality abnormalities is dependent on the characteristics of the water and on the 'background noise' variability of the monitoring location.

The monitoring location has a significant impact on the detection of contamination events, and the configuration of the EDS for the individual monitoring station should rely on the water utility's experience and should be adjusted during the implementation process. Unique monitoring stations with specific site profiles should be established by the utility, if necessary. The EDS can calculate probability according to the variation of the water-quality signals and, as a result, can reduce the false events at a typical noisy monitoring station.

The utility has to decide on the frequency of the data transfer according to the energy limitations of the LE sensors.

5.6.4. Fourth stage — operation

The fourth stage, after collecting a certain minimum amount of data from different stations, is to carry out offline and online analysis of valid and invalid alerts and learn how to classify events with the EDS developer.

5.6.4.1. Events

EDS must be reviewed regularly to support operations and event detection.

An event may occur when there are changes in the water quality or operational-sensor measurements are outside the range of values or in violation of some rule of the EDS. Events may occur because values are:

- outside regulation limits;
- outside the utility's limits;
- outside statistical limits;
- outside other statistical rules, e.g. rate of change, rare frequency;
- without normal change;
- missing.

The EDS should recognise different events caused by communication problems and provide an alert accordingly for:

- voltage problems with the sensor controller;
- communication interference;
- missing data;
- delays in data transfer;
- incorrect data transferred.

The last three may be caused by cyberattack.

The EDS should be able to provide an alert about a situation involving an unusually high frequency of events within a specified period of time.

The EDS should have an ID number and time stamp for each event.

An event ends when none of the above conditions exists.

Events can be presented on a GIS map also showing the CWQM stations, lines and other hydraulic accessories.

At this stage, when an alert is received, qualified utility personnel follow the procedures to identify its cause: reviewing information in the EDS/SCADA (the parameters violated and how, the event start time, the event profile — the shape of the curve, steep or flat/gradual stepwise curve, the length of time and the level) and other connected information-management systems; conducting an on-site investigation of the sensors

and the communication devices; taking a water sample at the monitoring station; testing it using portable meters or in the laboratory; and comparing the results with the online monitoring system.

When the cause is known, classification of the event according to the classified possibilities of the EDS should be carried out as near as possible to the time of the event's occurrence. Classification of the event as invalid or valid, with the cause written up, will improve the EDS's machine learning.

If the alert is determined to be a real incident, it may be necessary to take corrective actions according to the utility's water-safety plan.

5.6.4.2. Event cause

The water quality in the distribution system is complex and variable, and invalid alerts will persist. The utility's expertise will be needed to interact with the EDS and to reject invalid alarms so they are not shown again.

Analysis must be performed to determine if the event alarm is real and if it is true positive (TP) or false positive (FP). The utility has to investigate the event and identify the possible or known causes behind it (sometimes no reason is found and then the cause will be unknown) and classify it accordingly.

There are many possible benign causes for anomalous parameter values that can produce invalid alerts. Some such causes are the malfunctioning of a sensor, operational changes in the water network, reported/unreported network maintenance jobs or faults, communication problems, software malfunction, etc.

The route of inquiry of an alert includes checking all the data appearing in the EDS, information from other sources such as operation works, security alarm system and customer complaints, and physically checking the sensors in the CWQM stations.

The inquiry of the event should include but is not limited to:

5.6.4.2.1.Event-detection system

- If the event includes different quality and operational sensor alerts.
- The characteristic of each parameter change: the value, duration time, the shape of the parameter graphs (the typical shape of a contamination water-quality parameter curve presents a characteristic rise time, a plateau of stabilisation and a drop off).
- If the shape of each parameter graph is unusual a few days prior to and after the event graph change.
- The long-term, normal shape of each parameter graph in the event site.
- Which various EDS smart tools react and how they do so.
- If there is an alert in sequential CWQM stations, upstream and downstream of the event station.
- If the SCADA/EDS servers and cloud server connections are working properly.
- If the data transfer to the EDS is working properly and there is no indication of no data or fix repeated data (the EDS should sound an alert if there are data problems and report when data communication is restored and the values return to normal).
- If the EDS algorithms are functioning properly.

5.6.4.2.2. Continuous water-quality monitoring system

- The reporting monitoring sensor station is free of fouling.

- The water-flow rate and sensor pressure are as recommended.
- There are no air bubbles in the system.
- There are enough reagents as required by the sensors, or even better the system does not require reagents (optical measuring devices).
- The sensors in the CWQM are functioning properly and are calibrated using portable meters.
- With sensors based on a grab sample for testing, is the sampling system operating properly, with no blockage or leakage?
- If the communication between sensors and SCADA/EDS is working properly and there is no indication of no data or without normal change in the data.
- No recalibration of sensors.

5.6.4.2.3. Operational events

- No changes in treatment plant operations, different chemicals being used, such as disinfection material, or the control systems responsible for the addition of treatment chemicals.
- No unusual weather conditions or changes in temperature.
- No switch in source of water or fault in source water quality.
- There were no hydraulic changes or sudden jumps in water demand.
- There was no work being done in the water network on pipes, pumps, valves or pressure-reducing devices connected to the event-monitoring station.
- There was no maintenance work being done in the water network, such as hydrant flushing or reservoir cleaning connected to the event-monitoring station.
- There were no water-pipe breaks or failure of a booster station.

5.6.4.2.4. Other information sources

- If there is a security system alert.
- If there is physical evidence in a water installation of entering and tampering. If there are multiple customer complaints, concentration of complaints in a specific area.

In some cases there is no distinguishable cause for the event and/or the alert (no significant water-quality parameter changes have occurred).

5.6.4.3. Event classification

Events can be classified into four types: TP abnormal events correctly identified as abnormal events, FP normal events incorrectly identified as abnormal events, TN (true negative) normal events correctly identified as normal events and FN abnormal events not identified. TN is not actually an event and it is impossible to classify FN as there is no event alert. An artificial known event may be checked by means of a simulation for detection. The rate of each type is determined by its percentage.

The utility should build up a classification table based on local knowledge of the network and its operational activities, and similar previously classified event causes. The different event causes will be correlated to the type of the event. The utility will decide how to classify the events, the severity of each event and if the machine learning algorithms will learn this event or not.

The same event pattern may have different causes. The same cause may show different event patterns.

Some causes are known in advance, such as sensor maintenance and initiated maintenance networks.

The classification table may be unique to the utility and should cover all possible causes throughout the related distribution system.

Some examples for event investigation and classification, and the response needed, are included in the following section.

5.6.4.3.1. False positive events

- Event pattern: only turbidity increased in a monitoring station in a pressure-reducing station.

  Cause found: dirt/air bubbles in the sensor monitoring system.

  Classification: FP event — the system detected an event (positive) but it was caused by dirt/air bubbles in the monitoring system (false), which may be typical of this site (machine learning — yes).

  Corrective action: cleaning the monitoring system more frequently or trying to prevent the creation of dirt/air bubbles in the site, or finding another water-feeding source for the monitoring system.

- Event pattern: turbidity increased, pressure increased in a reservoir.

  Cause found: pump operation.

  Classification: FP event — the system detected an event (positive) but it was caused by a disturbance when the pump started to operate (false), which may be typical of this site (machine learning — yes).

  Corrective action: teaching the EDS software to recognise this pattern and not sending an alert regarding this phenomenon, and/or finding a solution to neutralise the disturbance.

- Event pattern: only turbidity increased in a monitoring station on the pipeline network.

  Cause found: the definition of the turbidity parameters of the EDS is too sensitive.

  Classification: FP event — the system detected an event (positive) but it was caused by an inaccurate variable definition (false), which may be changed to the correct one (machine learning — no).

  Corrective action: adjusting the turbidity parameters of the EDS.

- Event pattern: turbidity increased, free chlorine decreased, pH decreased in a reservoir.

  Cause found: sensor maintenance and calibration.

  Classification: ignore event as it is an FP event — the system detected an event (positive) but it was caused by known sensor maintenance (false) and known maintenance work. Ignore event (machine learning — no).

  Corrective action: ensure the sensors are operating properly.

- Event pattern: turbidity increased, free chlorine decreased in a monitoring station on the pipeline network.

  Cause found: pipe-maintenance works.

  Classification: FP event — the system detected an event (positive) but it was caused by known pipe works (false), known operations or another event (machine learning — yes).

Corrective action: ensure the quality of the water at the end of the work.

5.6.4.3.2. True positive events

- Event pattern: turbidity increased, free chlorine decreased, TOC increased in a monitoring station on the pipeline network.

  Cause found: unknown in the beginning, contamination found according to laboratory results.

  Classification: TP event — the system detected a true event (positive), which was caused by contamination in the water network (true). Real contamination event (machine learning — yes).

  Corrective action: according to emergency contamination event procedures of the water safety plan.

- Event pattern: free chlorine is low in the treatment plan.

  Cause found: problem in the disinfection process.

  Classification: TP event — the system detected an event (positive), which was caused by a known problem in the disinfection process (true). Real known operational event (machine learning — yes).

  Corrective action: correction of the part which caused the problem.

- Event pattern: turbidity increased, free chlorine decreased, pressure decreased in a monitoring station on the pipeline network.

  Cause found: pipe break.

  Classification: TP event — the system detected an event (positive), which was caused by what was later found to be a pipe break (true). Real unknown operational event (machine learning — yes).

  Corrective action: correct disinfection of the pipe.

- Event pattern: turbidity increased, pressure decreased in a monitoring station on the pipeline network, and customer complaints about low flow and turbidity.

  Cause found: pipe break.

  Classification: TP event — the system detected an event (positive), which was noticed due to customer complaints and was later found to be a pipe break (true). Real unknown operational event (machine learning — yes).

  Corrective action: correct disinfection of the pipe.

5.6.5. Fifth stage — final adjustment and running

The fifth stage is when enough historical data, including water anomalies of valid and invalid alerts, is collected and used as a baseline to adjust configurations until acceptable performance and correct operation are achieved.

The adaption and calibration of the EDS rely on sufficient data. The larger the amount of historical data the more accurate the EDS will be.

Judicious selection of various parameter settings within the EDS will impact the number, accuracy and precision of the FP and FN alerts.

The utility needs a policy to decide on the trade-off between the sensitivity and invalid alerts and adjust the EDS configuration of the EDS variables (such as alert thresholds, time), to balance and reduce the number of such alerts but not reduce the sensitivity of the system, causing real events to be missed.

The utility should set the values based on experience and common practices, using the data, and decide on the acceptable minimum detection percentage.

The EDS should have the ability to perform contamination simulations. Contaminant types and concentration should be checked by simulation in the EDS. They may have an impact on the detection and configuration fine tuning may be needed accordingly.

Classification of events according to the causes should be done daily in the software by trained authorised utility operators, in order to facilitate EDS machine learning. Later, each TP event should be approved by authorised expert personnel.

It is recommended that a classification library, which contains examples of all types of classified events that occur in the utility network — including graphs and an explanation of the logic behind the classification, be established. The library will be a guide for the interpretation of events based on the classification process to determine the urgency with which an input into the decision-making process should be made, and will be a training tool for users.

The EDS should be able to compare the similarity between the set of parameter measurements of a current event and that of past events that have been classified, and automatically classify it accordingly. The EDS can be trained in the variations of water-quality parameters in a monitoring station and will no longer sound an alarm during these regular periods of change.

The utility needs a learning policy for minimising false alerts based on the accumulation of classified events. The policy defines the utility's authorised persons, what changes of the different variable values appearing in the EDS (such as thresholds, algorithm criterions) should be made (changes can be for one quality parameter or a specific site) and when they should be made (a large enough number of classified events or a running period). Every change should be made with the EDS expert to ensure that there is no influence on the software or by the EDS expert if the changes are in the software. The policy can include a periodic review of the classified events, also using specific reports produced by the EDS software to examine the reliability and accuracy of the classification process, the comparison of event causes and types between monitoring sites, and to decide on specific classification rules and other recommendations for changes.

The water utility should be aware that the existence of the EDS cannot guarantee that the event's causation and/or consequences for service provision will always be quickly recognised before a third party is affected.

5.7. Maintenance

Sensor hardware and communication problems trigger a large percentage of invalid alerts. Proper maintenance of the sensor is crucial to reduce invalid alerts and maximise the EDS's ability to detect water-quality anomalies in the distribution network. To that end, existing software to validate data and to classify events would help a lot.

The utility should develop procedures and tasks and appoint employees to effectively and efficiently operate and maintain the EDS system. Alerts should be regularly reviewed, configurations updated as necessary (particularly important if standard water-system operations have changed) and EDS parameters and procedures updated based on lessons learned. Sensor manufacturers may also help with that work if a remote connection is allowed by the water utility.

5.8. The utility's response

The utility must develop a well-thought-out procedure for dealing with a water contamination event. This SOP must be learned by all relevant personnel and must be drilled, modified and periodically reviewed. All of this is in order to minimise the effective response time. Once an alert has been received, and after EDS and water-quality

personnel have estimated that the alert points to a serious water-quality issue (based upon, among other considerations, historical documented information), the alert should be passed on to operations personnel designated to deal with a water-contamination event. A decision on further monitoring should be made where the event may require a crisis-management response.

When the investigation into the cause of an alert indicates the possibility of contamination, rapid field tests and laboratory tests should be carried out. The type of laboratory tests ordered may be derived from the information generated by the CWQM system, thus shortening the time to achieve meaningful results. The laboratory results may also help to determine a root cause of the detected event.

Post-event evaluation of the EDS should be carried out in order to establish the validity of the output and to improve the event-detection process.

5.9. Quality assurance, verification and documentation

The purpose of software verification is to ensure that specifications are adequate with respect to intended use and are correctly, accurately and completely implemented.

The software-verification quality-assurance procedures will include the offline and online EDS; the implementation and maintenance of the software; and tests to ensure data, data-transfer, and performance-acceptance criteria are met as expected along the way and according to the requirements.

To evaluate the performance of an EDS with respect to an FP or FN, it is necessary to gather historical data on a significant number of events. However, since there are often not enough events available, it is recommended that the offline simulation of events (different contamination scenarios) be used on top of the utility’s true historical water-quality data in order to evaluate the performance of the EDS.

It is important to verify that the EDS is functioning properly. This verification should include the integrity of all data streams: transfer, processing and responding; alert analysis; and integrity testing.

Measured values in the data should be checked and relevant factors, technical problems and operational changes should be considered. Verify that:

- physical limits of the sensors have not been violated;
- the data received is constantly changing and is not fixed;
- there is no data missing;
- rates of change of a variable are credible;
- the duration of the change of a variable is significant;
- no fixed repetitive patterns are present;
- each variable presented is compatible with historical data;
- raw-data backup is in place.

Verification should be carried out periodically and also whenever any major change is made in the software or to the data streams.

The purpose of this is to verify that the rules and algorithms of the EDS are functioning correctly and can detect events.

Verification is carried out by analysing artificial or historical data and/or by simulating various scenarios of different events, or by the physical introduction of surrogate chemicals or contaminants in a separate test site hermetically isolated from the water network in order to prevent contamination of the real distribution system.

Verify that sensors are maintained and calibrated according to the proper procedures, and check (using a small sample of data) that the data generated by the sensors on site is indeed fed into the EDS.

Post-event evaluation of the EDS should be carried out in an attempt to establish the validity of the output and for continual improvement of the event-detection process.

All data transfers and access to the EDS shall be in accordance with appropriate data-security standards.

All changes in the EDS should be documented. This includes:

- events and their classification and any change to event details;
- changes to the variables and parameter values of the EDS, such as thresholds, times, severity, rules, etc.

6. The water quality contamination dissemination look-ahead simulation model

6.1. Contamination dissemination look-ahead simulation model — the need and the benefit

The CDLAS model is an adaptation of the hydraulic model which allows the user to see graphically the areas and pipes affected by a given contamination at different hours after introduction (Bernard, 2016; Bazargan-Lari, 2018). The hydraulic model in turn requires detailed and complete physical information on the pipe system, and this information is most readily available and maintained in a GIS system.

The CDLAS model is a DSS. This means that the model displays the possibility of a contaminant's path and time of dissemination, but it requires broad engineering knowledge of the water system and its operation in order to apply the model's information to make operational decisions. The model's power is in its user-friendly representation of information, which is vital for proper decision-making; the model itself does not provide answers or make decisions.

There is a possibility for offline and online CDLAS models.

A reliable CDLAS model should be connected to the online data of the water-distribution system — water demand, reservoir levels, etc. This information is available in other systems: reservoir levels and other operational data are collected by SCADA systems; water consumption is available in the SCADA system and/or from automatic meter-reading systems. This achieves a more true-to-life analysis of the contaminant's dissemination and makes the simulation much more relevant and real as opposed to an offline simulator.

An advanced, online dissemination model, coupled with CWQM stations located in the piping system, can carry out a sort of 'reverse engineering' routine in order to indicate in which area and in what time span a contaminant was introduced. This ability of the model is achieved by comparing the reports of two or more sensors regarding the time the contaminant reached that sensor. Since the CDLAS model knows the flow rates and directions, it can 'look upstream' of the sensors and calculate from which area the contaminant must have come and in what time span. Such an advanced feature then allows the operator to make an intelligent guess as to the source of the contaminant, thus achieving more accurate results from running the CDLAS model.

The CDLAS model should include:

- an option to set the start date and time of the scenario according to the water flow and demand;
- a display of flows in pipes for corroborating the online data;
- a display of pressures at nodes and at CWQM stations, for checking and calibrating the model against real pressure measurements from the field;
- a display of system valves to be closed in order to isolate contaminated areas of the network and halt the advance of the contamination;
- a display of hydrants to remove contaminated water from the distribution system;
- a display of locations in the network to inject decontamination agents to inactivate or remove contaminants;
- the ability to create and display a dynamic list of locations in the network to take a grab sample to confirm contamination or clean-up.

6.2. Implementation

The CDLAS model is fairly expensive and time-consuming to create. The utility may however create the CDLAS as an enhancement of a conventional hydraulic model, as part of creating the utility's master plan for the distribution system. The further development of a hydraulic model into a predictive tool requires the development of a human–machine interface to allow the operator to use the model efficiently. It is also vital that the model be enhanced to receive online operational information. This type of interface is still rare today and requires particular effort and funding.

The use of a CDLAS requires capable engineers who are well versed in the water system and its operation.

6.3. Using the contamination dissemination look-ahead simulation model in a real emergency situation

An online CDLAS model allows the user to run simulations of contamination events in the water system and to map the expected dissemination of the contaminant in the water system. Understanding the dissemination vector is vital for controlling and mitigating a contamination event, thus saving lives and limiting damage.

In a typical emergency situation, the utility will receive some indication of a contaminant entering the system. This information may come from security systems, water-quality sensors (CWQM), customer complaints, etc. The first step in using the CDLAS model is to feed the model with information about where and when the contaminant was introduced into the water system. Most of the time this information is not actually known. Nonetheless, the event manager must decide or assume where and when the contaminant was likely introduced and input this information into the model. There are other DSS systems that can aid in this task.

Secondly, the CDLAS model must be updated with current operational data. This is done automatically if the model has been designed 'online'.

The operator then runs the model and receives graphical output indicating which pipes will have been contaminated by what hour after introduction.

This information must then be critically applied when deciding on actions to be taken to lessen the impact of the dissemination. Typically this would involve stopping or starting pumps, closing down reservoir tanks and/or closing line valves in order to contain the contaminant at a particular 'front'. Further development of the CDLAS could include the ability to import valve locations from the GIS system. This would enable the operator to choose a 'front' where they wish to halt dissemination (e.g. 3 hours from now, which is the time required to route field crews and close the valves), and the model would then present the valves to be closed at points where the contaminant has not reached 3 hours from now).

Once the event manager has taken steps to halt or limit the contaminant's spread in the system, they must assess whether or not the steps taken have succeeded in isolating and halting the spread of contamination.

They must first send out crews to sample the water within the 'front'. These tests must be positive for some indication of contamination; in this way, we will know that the particular test used can indeed reveal the contamination. Once we have a field test that is able to reveal the contamination, we would sample water beyond the 'front' in order to ascertain whether the actions taken did indeed halt the spread of the contaminant. If any of these tests are positive, we have erred in the task. If time permits (i.e. the area in question is so large that many hours will elapse before a contaminant can reach the ends of the system) the model can be rerun and a further 'front' located, and so on.

6.4. CDLAS simulations

In order to better understand the direction of the water flow in the water network and to find the most severe scenarios in which the population is exposed before detection, the utility's personnel can run simulations with various strategic locations for the introduction of a contaminant, different contaminants and concentrations and different times of contamination, during different water-consumption periods etc. Examining the contaminant spread for these scenarios will vastly improve engineers' knowledge of the water system.

To run the CDLAS model the utility should define the test area and have all the required details of the scenario's simulation parameters (date, hour, length of simulation run, points of injection of contaminant).

The CDLAS model already includes the length of pipes; the location of reservoirs, pump stations and other water facilities; CWQM stations; the supply source; flow-rate system pressure; and the population size.

It is important to analyse the results and check if the time of arrival values calculated by the model for each sensor were logical:

- what the time of detection at each sensor location for each scenario was;
- which pipelines were contaminated;
- what population was exposed to the contaminant before it was first detected.

Both offline and online CDLAS simulation results may be represented by showing on the network map the spread of the contamination as a series of colours. Each colour may represent pipes with:

- different contamination concentrations, assuming a certain decay factor (in practice the contaminant and the decay mechanism are not known);
- different contamination-spread time steps according to the spread of the contaminant hour by hour, over the entire time period chosen.

6.5. Maintenance and calibration

In order for the model to maintain its relevance to the water system, the utility must constantly update pipe data and water-use data in the model. Network-information changes should be fed into the model in order for the model to be accurate and relevant. If this is not done, the model soon loses relevance.

The operating personnel should be trained and should carry out exercises periodically so that they are ready to handle an emergency situation immediately and professionally.

The CDLAS is based on a hydraulic model, which in turn requires detailed information regarding the pipe system and the water-use profile. Such information, imported into the model, allows the model to calculate flow rates and pressure losses in the system. In order to ascertain that the model is a true and accurate representation of the water system, it must undergo calibration, that is, the model's predictions must be compared with true-field measurements of flow and pressure. Should the model's predictions not be in line with true measurements, the model (physical data) must be adjusted accordingly. Calibration of a CDLAS model is a difficult, time-consuming and expensive process. The water engineers' expertise and experience are therefore doubly valuable.

7. Event-management system

The utility should consider installing an event-management system (EMS) (EPA, 2007, 2008; Philadelphia Water Department and CH2M HILL, 2013b; Bernard, 2016).

The EMS is a software platform designed to aid the water utility in detecting, providing an alert for and mitigating the damage of a contamination event in the water-supply network. The EMS continuously receives information from the EDS including contamination-event alerts. The EMS prompts the utility's event manager to deal effectively with the event based on pre-embedded task menus mirroring the utilities' own SOP and also runs a DSS in the form of online hydraulic and CDLAS models of the water-distribution system. As described above, the model can predict the dissemination path of a contaminant in the water system, thus allowing the event manager to take steps to halt the advance of the contaminant in the water system using a variety of actions, all prompted by the EMS.

No known complete EMS platform that interfaces with all other tools of the monitoring system, mentioned above, is available yet. Even if such EMS software were to exist, there is no standard solution and it would be the responsibility of the water utility to adapt the EMS to their environment and to the vulnerability of their water-distribution network, according to their plans (emergency, security plans, e.g. unique health- and water-authority rules, utility — reporting chain, SOPs, manpower resources, language).

7.1. Example of the features of the event-management system

An example of EMS features to support the execution of the utility's SOPs in the case of a water contamination event is shown below. It was derived from the results of the EU-funded FP7 Safewater project (Safewater, 2016).

The utility should bridge the gap between the overall description of the required tasks and the necessary details for an actual implementation.

Part one is event declaration and part two is event management.

7.1.1. Event declaration

This section presents the tasks to be carried out between the detection of a possible contamination and the declaration of a contamination event by one of the authorised members of the utility.

1. The EDS detects changes in the monitored parameters that may be produced by a contamination event. A drop in chlorine accompanied by an increase in turbidity is a typical example of suspicious changes.
2. The EDS sends an alert to the EMS.
3. The EMS stores the notification provided by the EDS and checks its severity. If the severity of the event is low, the event is recorded and waits to be processed as a 'normal' event. If the severity is high, the EMS automatically performs the following actions.
   (a) Displays the alarm on the graphical user interface using a combination of colour, text size and position to convey the severity of the event.
   (b) Automatically sends emails to the staff responsible.
   (c) Triggers the execution of the simulators.
4. An authorised staff member of the utility declares a contamination event in the EMS.
5. The EMS initiates the response actions.

Currently, the severity evaluation performed under bullet number 3 above is conceived as a simple check on the attributes of the received alarm that will return a binary answer. Such an evaluation may be replaced by a decision scheme based on a rule set that could affect the execution of certain tasks or even give rise to the execution of a completely different workflow. Aspects that should be considered for severity evaluation include the population of the affected area(s) and the presence of sensitive infrastructure such as hospitals or schools, as revealed by running the simulation models.

6. Simulations

The simulations started as a response to a high-severity alarm are the following.

(a) Source identification to estimate the location on the network where the contamination originated.

(b) Forward simulation to estimate the spread of the contamination in the water system.

(c) Third simulation module capable of recommending what valves to close to prevent contamination spread.

The execution of the simulations is based on a small separate workflow. The simulators' results will be displayed in the GIS component of the EMS.

The simulation workflow may be extended with input forms (or equivalent mechanism) to enable workers in the field and the utility's personnel to communicate changes in the network, for example valves that have been closed or pumps that have been stopped. Such changes would be forwarded to the simulator modules in order to update the models with the current state of the network.

On the display showing the simulation results a range of colours is used to represent graphically the values of a certain parameter across the network over a range of times. An alternative view, in which concentric areas are drawn on top of the GIS representation of the pipe network to represent the forecast evolution of the contamination spread at different points in time, may also be a very useful tool to plan response actions.

7.1.2. Event management — first stage — immediate action

1. When the event is declared, the EMS automatically performs the following actions.

   (a) Sends messages (email, SMS, etc.) to the emergency-situation-room team members to have them convene, including the first information about the event.

   (b) Displays 'Stop Water Flow in Affected Area' box on top of the active view and sends an automated message to operations personnel with the first information about the event and a reminder to stop/limit water flow.

2. An authorised user enters the available information about the problem.

3. Takes action to notify appropriate authorities (health, regulatory and security).

4. A public relations (PR) member selects and fills in the appropriate template for answering consumer calls to the utility's call centre and for a press release.

5. The information generated from the edited template is made available to the call centre.

7.1.3. Event management — second stage — continuing actions

To support decision-making, the EMS provides a central location where all information regarding the ongoing event can be gathered. This central point of information reflects the current situation and documents planned actions. Initially, such information will be introduced as free text. Later on, these concepts may be modelled in the system in order to provide a more structured and systematic approach. An important aspect of the system is the capability to log these updates and enable analysis of the response actions once the emergency situation is over.

Some response actions that may be clear or even obvious under normal circumstances may be forgotten under the high stress caused by a contamination emergency. In the EMS, it will be possible to create checklists to ensure all required actions are performed.

A lot of actions take place during this phase and their results should be included as a situation update. The aforementioned checklist mechanism could be used to explicitly reflect them in the EMS. Specific forms may be set up if necessary.

In the following paragraphs, the performance of the tasks included in the second stage, as listed in the utility's SOPs, is discussed from the perspective of the EMS. In this case, the numeration does not imply a particular order.

1. Define the area affected, predict the contamination spread, recommend actions (valves, pumps, etc.)/update models with new input: to support decision-making, simulation results to show the affected area and its evolution will be displayed, as explained in Section 7.1 of this document. The ability to provide recommendations and update the models will depend on the capabilities provided by the simulators.
2. Produce a situation report and operational plan: will be supported by allowing the users to extend the event information with a new situation update introduced as free text (the EMS should provide the template for the above report and plan, with a prompt to update the report every N hours). A more structured and systematic approach may be attempted.
3. Verify that the contamination is real: the results of this task will be added to the event as a situation update.
4. Initiate the investigation of a cause of contamination and inform the police if necessary. May be represented in the system as an action item in a checklist.
5. Inform the public and key players: as new information becomes available, the personnel in charge of PR, with appropriate technical support to analyse the situation, will evaluate communication needs and produce the corresponding reports with support from templates stored in and editable through the EMS. The EMS will enable their distribution or publication as a web page. The EMS should also prompt press releases and press conferences. The EMS should remind the event manager of the importance of ongoing updated PR.
6. Initiate water-quality testing (check if the isolation of the contaminated zone has succeeded): the results of this task will be added to the event as a situation update.
7. Present the alternative water supply system as an action item in a checklist. Ideally, a dedicated workflow and organisation to deal with this measure should be triggered.
8. Coordinate with the health authority to gather samples and identify the contaminant. May be represented in the system as an action item in a checklist.

7.1.4. Event management — third stage — follow-up actions

A number of measures are included in the third stage which may be supported by the EMS.

1. Organise utility personnel for continued operations.
2. Organise a continued alternative supply of water to the isolated area.
3. Continue PR activities.
4. Start a ‘sanitary field survey’: may be represented in the system as an action item in a checklist. Specific forms may be set up if necessary.
5. Mark valves that must not be opened: an operation may be implemented to virtually mark/unmark such elements in the GIS view.
6. Run a hydraulic model to analyse continued effect of closed valves: included as part of the integration with the simulators.

8. Conclusions

This guidance is complementary to the water-security plan, which is developed by this ERNCIP Thematic Group in order to address the risk of intentional or accidental contamination of drinking-water-distribution systems (Weingartner and Raich-Montiu, 2015; Hohenblum *et al.*, 2016).

CWQM is a proactive approach for monitoring water quality for potential contamination, both accidental and intentional, through the deployment of advanced technologies and enhanced monitoring to collect, integrate, analyse and communicate information, and is a fundamental element of the water-security plan.

This guidance describes the design and implementation process of a CWQM system in a water utility. Major points to be considered by the utility before and during the implementation are described for each required component of the system, namely the hydraulic model and GIS application, sensor-placement optimisation software, the sensors, the EDS, the water quality, the CDLAS model and the EMS.

To implement such a system, water utilities must weigh the costs and benefits of various designs and understand the significant public-health and cost trade-offs. This document provides the practical basis for such a project to be initiated and highlights the need for the water utility's multiple stakeholders to collaborate with each other.

References

Bazargan-Lari, M. R. (2018) 'Real-Time Response to Contamination Emergencies of Urban Water Networks', *Iranian Journal of Science and Technology, Transactions of Civil Engineering*. Springer International Publishing, 42(1), pp. 73–83. doi: 10.1007/s40996-017-0071-2.

Bernard, T. (2016) 'Safewater Innovative tools for the detection and mitigation of CBRN related contamination events of drinking water', in *Water Safety and Security Workshop*. Brussels. Available at: http://www.safewater-project.eu/images/161212-Safewater-Presentation-T-Bernard_v2.pdf (Accessed: 30 July 2018).

Brill, E. and Brill, B. (2016) 'Identifying Water Network Anomalies Using Multi Parameters Random Walk: Theory and Practice Provisional chapter Identifying Water Network Anomalies Using Multi Parameters Random Walk: Theory and Practice'. doi: 10.5772/intechopen.71566.

Clark, R. M., Hakim, S. and Ostfeld, A. (2011) *Handbook of water and wastewater systems protection*. Springer.

Drinking Water Inspectorate (2009) *Guidance on the Notification of Events, V.3*. Available at: http://www.dwi.gov.uk/stakeholders/guidance-and-codes-of-practice/notification of events.pdf (Accessed: 1 August 2018).

EPA (2007) *Water Security Initiative: Interim Guidance on Planning for Contamination Warning System Deployment, EPA 817-R-07-002*. Washington, DC: United States. Environmental Protection Agency. Available at: https://www.hsdl.org/?abstract&did=34212 (Accessed: 26 July 2018).

EPA (2008) *Water Security Initiative: Interim Guidance on Developing Consequence Management Plans for Drinking Water Utilities, EPA 817-R-08-001*.

EPA (2010a) *Sensor Network Design for Drinking Water Contamination Warning Systems: A Compendium of Research Results and Case Studies using the TEVA-SPOT, EPA/600/R-09/141*. Washington, DC.

EPA (2010b) *Water Quality Event Detection Systems For Drinking Water Contamination Warning Systems: Development, Testing, and Application of CANARY, EPA/600/R-10/036*. Washington, DC.

EPA (2013a) *Data Set: Water Quality Parameter Response Data for 5 Different Finished Drinking Waters from 4 Large Municipalities, EPA/600/R-13/179*. Washington, DC.

EPA (2013b) *Water Quality Event Detection System Challenge: Methodology and Findings, EPA 817-R-13-002*. Washington, DC.

EPA (2014a) *Configuring Online Monitoring Event Detection Systems, EPA/600/R-14/254*. Washington, DC.

EPA (2014b) *Water Security Toolkit User Manual: Version 1.3, EPA/600/R-14/338*. Washington, DC.

EPA (2015) *Online Water Quality Monitoring Primer For Water Quality Surveillance and Response Systems, EPA 817-B-15-002A*. Washington, DC.

EPA (2016) *EPA's Water Security Modeling and Simulation Research, EPA/600/S-11/007*. Washington, DC.

van der Gaag, B. and Volz, J. (2008) *Real-time online monitoring of contaminants in water: Developing a research strategy from utility experiences and needs, BTO 2008.028*. Available at: http://www.waterrf.org/Pages/Projects.aspx?PID=4025 (Accessed: 26 July 2018).

Gattinesi, P. (2018) *European Reference Network for Critical Infrastructure Protection ERNCIP handbook 2018 edition.* Luxembourg: EUR 29236 EN, Publications Office of the European Union. doi: 10.2760/245080.

Geetha, S. and Gouthami, S. (2016) 'Internet of things enabled real time water quality monitoring system', *Smart Water*. Springer Singapore, 2(1), p. 1. doi: 10.1186/s40713-017-0005-y.

Ginther, P. (2007) *Use of GIS Growing in the Municipal Water, Wastewater Business*, *WaterWorld*. Available at: https://www.waterworld.com/articles/print/volume-23/issue-4/editorial-feature/use-of-gis-growing-in-the-municipal-water-wastewater-business.html (Accessed: 30 July 2018).

Hall, J. *et al.* (2007) 'On-line water quality parameters as indicators of distribution system contamination', *Journal / American Water Works Association*, 99(1), pp. 66–77. doi: 10.1002/j.1551-8833.2007.tb07847.x.

Hohenblum, P. *et al.* (2016) *Proposals for a guidance related to a Water Security Plan to protect Drinking Water: ERNCIP Thematic Group Chemical and Biological (CB) Risks to Drinking Water*. doi: 10.2760/258130.

IEC (2018) *International Electrotechnical Vocabulary*. Available at: http://www.electropedia.org/ (Accessed: 30 July 2018).

ISO (2003) 'ISO 15839:2003 — Water quality — On-line sensors/analysing equipment for water — Specifications and performance tests'. Available at: https://www.iso.org/standard/28740.html (Accessed: 26 July 2018).

ISO (2018a) 'ISO/DTS 24522 — Water quality event detection process: Guidelines for water and wastewater utilities [under development]'. Available at: https://www.iso.org/standard/59813.html (Accessed: 25 July 2018).

ISO (2018b) 'ISO/WD TS 24541 — Services activities relating to drinking water supply systems and wastewater systems —Guidelines for the implementation of continuous water quality and operation mode monitoring system in a drinking water network [under development]'. Available at: https://www.iso.org/standard/74482.html (Accessed: 26 July 2018).

Ostfeld, A. *et al.* (2008) 'The Battle of the Water Sensor Networks (BWSN): A Design Challenge for Engineers and Algorithms', *Journal of Water Resources Planning and Management*, 134(6), pp. 556–568. doi: 10.1061/(ASCE)0733-9496(2008)134:6(556).

Panguluri, S. *et al.* (2009) *DISTRIBUTION SYSTEM WATER QUALITY MONITORING: SENSOR TECHNOLOGY EVALUATION METHODOLOGY AND RESULTS*. Washington; DC. Available at: https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=212368 (Accessed: 25 July 2018).

Philadelphia Water Department and CH2M HILL (2013a) *Philadelphia Water Department Contamination Warning System Demonstration Pilot Project: Guidance for Locating Online Water Quality Monitoring Stations Using TEVA-SPOT*. Available at: www.ch2mhill.com/iws (Accessed: 26 July 2018).

Philadelphia Water Department and CH2M HILL (2013b) *Philadelphia Water Department Contamination Warning System Demonstration Pilot Project: How to Select an Online Water Quality Monitoring Data Management System.* Available at: www.ch2mhill.com/iws (Accessed: 26 July 2018).

Preis, A., Whittle, A. and Ostfeld, A. (2011) 'Multi-objective optimization for conjunctive placement of hydraulic and water quality sensors in water distribution systems', *Water Science & Technology: Water Supply*. IWA Publishing, 11(2), p. 166. doi: 10.2166/ws.2011.029.

Public Utilities Board Singapore (2016) 'Managing the water distribution network with a

Smart Water Grid', *Smart Water*. Springer Singapore, 1(1), p. 4. doi: 10.1186/s40713-016-0004-4.

SABE (2018) *Standardization needs in continuous water quality monitoring — Strategic Position Paper, SABE ENV N 333*.

Safewater (2016) *Innovative tools for the detection and mitigation of CBRN related contamination events of drinking water*. Available at: https://www.safewater-project.eu/ (Accessed: 30 July 2018).

Thompson, K. E. *et al.* (2011) *Optimal Macro-Location methods for sensor placement in Urban Water Systems: Literature Review, D3.5.1, Report no. PREPARED 2011.004*. Available at: http://www.prepared-fp7.eu/viewer/file.aspx?fileinfoID=171 (Accessed: 26 July 2018).

Wagner, R. J. *et al.* (2006) *Guidelines and standard procedures for continuous water-quality monitors—Station operation, record computation, and data reporting: U.S. Geological Survey Techniques and Methods 1–D3*. Available at: https://pubs.usgs.gov/tm/2006/tm1D3/ (Accessed: 26 July 2018).

Weingartner, A. and Raich-Montiu, J. (2015) *Proposal for a water security plan to improve the detection of threats in the distribution network affecting drinking water quality: ERNCIP Thematic Group Chemical and Biological Risks to Drinking Water*. doi: 10.2788/63373.

List of abbreviations and definitions

2D/3D	two-dimensional/three-dimensional
CBRN	chemical, biological, radiological and nuclear
CDLAS	contamination dissemination look-ahead simulation
CWQM	continuous water-quality monitoring
CSV	comma-separated values
DSS	decision-support system
EDS	event-detection system
EMS	event-management system
FN	false negative
FP	false positive
GIS	geographic information system
GSM/GPRS	Global System for Mobile Communications/General Packet Radio Service
ID	identification
IT	information technology
LAN	local area network
LE	low energy
ORP	oxidation-reduction potential
pH	potential hydrogen — acidity value
PR	public relations
Profibus DP	Process field bus Decentralised peripherals
RI	refractive index
SCADA	Supervisory control and data acquisition
SIM	Subscriber Identity Module
SOP	standard operating procedure
TCP/IP	transmission control protocol and internet protocol
TOC	total organic carbon
TP	true positive
WAN	wide area network
WLAN	wireless local area networking
XML	extensible markup language

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