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Potable water security assessment – a review on monitoring, modelling and optimization techniques, applied to water distribution networks

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ABSTRACT

The paper tries to investigate some of the most important issues that need to be addressed to provide an integrated system for potable water security, in developed countries. It can be understood that in developing countries both supplied water quantity and quality are important for water security. According to the US Environmental Protection Agency, "water security is defined as prevention and protection against contamination and terrorism." Water quality safeguarding has been addressed by many researchers during the last decades trying to define ways to ensure water of proper quality for the public. As unexpected contamination events may occur in water distribution systems, early warning systems providing the water managers with enough time to act effectively need to be developed. These systems should include interconnected: (a) monitoring tools to monitor in real time at least the most crucial water quality characteristics; (b) modelling tools to simulate the transport of any harmful contaminant and calculate the variations of its concentration; and (c) optimization tools to define the optimal locations and density of the monitoring sensors and disinfection stations. The drinking water supply system addressed in this paper consists of the supply system after the water treatment plant and until the consumers' taps, with special emphasis on the water distribution system. Drinking water security is addressed in cases other than normal operating conditions. Specifically, the paper examines contamination phenomena due to operational failures (e.g., during the disinfection process), natural disasters, pollution accidents and malicious actions. Contamination phenomena due to other factors, such as lead contamination are not included in this paper. It reviews the literature on monitoring, modelling and optimization techniques used in water distribution systems while at the same time proposes an integrated approach consisting of risk assessment methods and the use of "simheuristics" to deal with drinking water security.

Keywords: Potable water; Quality; Safety; Security; Disinfection; Optimization; Modelling

1. Introduction

Water is essential for the life of humans and ecosystems. Drinking water security (and not just safety) is today one of the most important issues, since various hazards (natural and man-made) may put public health in danger. The World Health Organization (WHO) recorded different waterborne diseases and water-related hazards. Drinking water security is recognized today as an intriguing challenge to deal with. Contaminated water can cause epidemic outbursts, interrupt economic life and create massive panic to the public. Water distribution systems (WDSs) are complex systems consisting of storage tanks, pipes, pumps, valves, fittings, meters and other devices, etc., most of them of different kind of materials and diameters, usually buried underground along a total length up to several hundreds of kilometres. The system's complexity and length make it extremely vulnerable to

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various different threats. Although the institutional framework developed for water quality is continuously improving, it has been observed that the methods used have a time lag in dealing with threatening events that negatively affect water quality.

Drinking water treated in raw water treatment plants contain a physical and microbial load and a reasonable number of nutrients when it enters the WDS. It is well known that drinking water quality changes as water travels inside the distribution system. Thus, although water quality is good after the water treatment plant, the interaction of water with pipes results in water quality degradation [1–4]. Thus, risk management techniques along with specific tools are used for the production and distribution of drinking water from its source to the final consumption point. The present paper aims at reviewing the literature regarding drinking water safety and security in WDS (after the treatment plant). The main threats are being identified and risk management techniques are being analyzed and reviewed. The paper focuses on threats existing due to sudden events (e.g., natural disasters, terrorism) and operational failures (e.g., disinfection, water age, etc.). The most important monitoring, modelling and optimization tools used are being reviewed. Finally, suggestions are provided toward the development of a reliable WDS to consumers including the efficient and effective early identification of risks and the proposal of crisis management solutions.

2. Factors affecting drinking water quality

Drinking water quality may be threatened by a number of factors, such as:

(a) operational failures in water distribution networks (including inadequate maintenance);
(b) natural disasters and extreme weather phenomena (e.g., earthquakes, floods, etc.);
(c) several types of accidents and contamination phenomena (e.g., spills due to tank truck accidents);
(d) malicious threats/terrorists' attacks (contaminating water with biological/chemical substances).

2.1. Operational failures in water distribution networks

Operational failures include water contamination events after network's repairs and disinfection failures. Water can be polluted if a contaminant enters a repaired pipe or due to sewage network pipes leaking. The latter is met when sewage networks lie above water pipes. In this case a leakage from a sewage pipe and at the same time a hole in the water pipe below may lead drinking water to be contaminated. There are other operational failures such as corrosion and lead contamination which are not examined in this paper.

Disinfection practices may also threaten drinking water quality when a failure occurs or even under normal operating conditions. Although chlorination is the most widely used disinfection method in WDSs, chlorine reacts with organic and inorganic compounds and with biofilm at the pipe walls and is consumed during the corrosion process. Whilst everyone recognizes the importance of water disinfection to safeguard public health, there is a concern regarding the possible side effects of disinfectants and chlorine use (or more accurately "over-use"), on consumers' health. Various chlorination by-products growth has been detected, especially when the doses of chlorine used are increased. Some chemical compounds found in water (e.g., humic, fulvic, hydrophilic and amino acids, carbohydrates, etc.) react with chlorine to form trihalomethanes (THMs) [5]. Today, THM side effects on humans' health are being studied in-depth, such as infertility, teratogenicity, kidney and liver inefficiency, effects on the nervous and hematopoietic system [6]. Several epidemiological studies focus on the harmful effects of chlorine by-products and link their increased concentrations with an increased risk of various forms of cancer growth [6]. Exposure to THM even via routes other than ingestion (e.g., skin contact) can put human health at risk. Hrudey and Fawell [7] presented an overview of the studies regarding disinfection by-products formation in drinking water supply systems.

During the last decades, water companies have put significant efforts to better manage their networks aiming at reducing real (physical) water losses. One of the most effective measure is to install pressure reducing valves to cut down these losses by reducing the operating pressure mainly during night hours [8–11]. However, the decrease of real water losses due to the pressure drop in the network results in an increase of the total time water remains in the pipes (i.e., water age factor) thus having inevitably a negative impact on its residence time, an indicator of its quality. The research of the specific negative impact is gaining more attention every day [12,13]. Increased water age is responsible for water quality deterioration due to interactions between supplied water and pipe walls [14]. Several factors such as water flow rate, water quality, pipe material and deposited material affect the level of water transformations (i.e., chemical, physical, aesthetic). A study conducted by USEPA [14] identified the water quality problems associated with water age, such as disinfection by-product formation and biodegradation, nitrification, microbial regrowth and recovery, having direct potential impact to human health. Other problems not affecting directly human health include disinfectant decay, taste and odour, temperature increase, colour, etc. [14].

2.2. Natural disasters and extreme weather phenomena

Natural disasters (e.g., earthquakes) and extreme weather phenomena (e.g., floods) may be the cause of water supply system failures and the transfer of contaminants to the water supply network. There are cases where water scarcity conditions exist and other cases where excessive amount of water is present at the wrong time, due to heavy rains and floods. In both cases human, economic and environmental damages could be the impacts of floods and/or water scarcity. Drinking water quality is affected due to earthquakes as the infrastructure may be damaged and the water may be contaminated.

2.3. Pollution accidents and contamination phenomena

Water quality affects the distribution pipes and at the same time the water distribution network itself affects water quality. The first case happens when the physico-chemical characteristics of the water running through water pipes may affect the WDS, as for example, soft water with low pH boosts corrosion of metallic parts [15]. The second case happens as the distribution system conditions may affect the quality of the water supplied, such as when pipe walls' leachates deteriorate the quality of the water [15]. Negative pressure can lead to contamination (i.e., disease-causing agent or a toxic chemical) in cases when a nearby fire exists, the network is shut down for maintenance, excessive water theft incidents or large main breaks take place. Cases of red water could denote the presence of iron either leaching from pipe walls or being present in the source. At network's dead ends resuspension of material deposited during low-velocity periods takes place. Water quality varies seasonally due to the water source conditions, negative pressure, or inadequate chlorine residual. Water quality alterations may be caused by the following problems: (a) presence of a particular contaminant (e.g., asbestos fibers leaching from asbestos cement pipes' walls); (b) bacterial contamination resulting from the absence of chlorine residual in conjunction with cross-connections, negative pressure or regrowth of resistant organisms. Water quality characteristics can also dramatically affect internal corrosion as high concentrations of soluble sulfates or chlorides (i.e., increasing electrical conductivity) exist in water; very soft water is highly corrosive; dissolved oxygen contributes to corrosion (i.e., formation of oxides); when low pH conditions exist, carbon dioxide dissolves with water and forms carbonic acid causing corrosion when combines with iron. Finally, contaminants can be introduced into the water from the wall of the pipe. The existence and rate of leaching depend on water quality characteristics (particularly pH) [15].

2.4. Malicious threats and terrorism

Since the beginning of time, water is often being used as a military or political target or tool [16]. As water has no substitute, it is a very attractive target for terrorists' attacks. Water supply can be a target for terrorists by attacking its infrastructure (i.e., dams, reservoirs, pipeline networks, etc.) or by forcing a contaminant to enter the water supply network (usually at the water tanks as water pipes are often pressurized). Physical attacks to infrastructure are easy to happen as major parts of the WDS are open and easily accessible to the public [16]. The last few years cyber attacks are also considered major threats, as hackers could take control of the automated operations of water utilities (e.g., supervisory control and data acquisition – SCADA systems). In this case water supply and water quality are both put in danger. Of course, both physical and cyber attacks can threaten any system and not only water supply ones. The most difficult type of terrorism attacks is the biological or chemical contamination which can theoretically take place anywhere in the WDS, but as already stated, practically at the water tanks as water pipes are often pressurized, thus harder to interfere with [16]. The best-case scenario is to on-time detect the presence of the biological or chemical contaminant and cut off the distribution of water downstream, alerting the consumers too. If this happens, citizens will not have access to water for some time. The worst-case scenario is not to detect, at least on time, the contaminant and people get infected (becoming sick or even die), while the economic life of the city gets disrupted resulting in serious health and economic damages. According to Gleick [16] and Valcik [17] biological treats include pathogens (i.e., bacteria, viruses) and toxins (i.e., chemical substances resulting from biological processes). Because of these hazards, drinking water security is increasingly recognized as a challenge and the need for systems supporting the prediction and management of water crisis events becomes one of the water utility top priorities [18].

3. Risk assessment and water security

Water security can have many dimensions. Cook and Baker [19] identified the quantity and availability of water; the issue of water-related hazards and vulnerability (including contamination and terrorism) [19–22]; human needs including food security, and human development-related concerns; water security as a component of food security; and sustainability. Cook and Baker [19] state that at the Second World Forum (in 2000), the Global Water Partnership introduced water security as "the access and affordability of water as well as human needs and ecological health." UNESCO on the other hand involves a system's approach and connects water security to the "protection of vulnerable water systems, protection against water-related hazards such as floods and droughts, sustainable development of water resources and safeguarding access to water functions and services" [19,23]. This paper focuses only to water security in the light of supply of safe, good quality drinking water to the water utility's customers. This means that this paper refers to developed countries and limits water security within the water supply and distribution network after the water treatment plant. Risk assessment is extremely important for water security. The system's vulnerability needs to be understood and assessed and at the same time adoption of mitigation measures to cope with the vulnerability and finally reducing risk is absolutely necessary [24]. Legislation exists at global, European and national levels and risk assessment tools are used by water utilities worldwide.

3.1. Institutional framework worldwide

To control the quality of the drinking water, an institutional framework has been established at both Global, European and national levels. Worldwide, the WHO provides the necessary relevant guidance. At the same time, it is suggested that risk assessment tools (i.e., hazard analysis and critical control points – HACCP, water safety plans) need be developed to identify possible respective risks. At European level, in addition to the Water Framework Directive 2000/60/EC, the Drinking Water Directive 98/83/EC has been in place regarding quality of water intended for human consumption, setting specific restrictions and contaminants' concentration acceptable limits.

At several countries at national level, existing institutional frameworks for drinking water quality include health provisions relating to water disinfection, provisions on monitoring the drinking water quality, including the frequency of monitoring, as well as provisions on the definition of responsibilities for drinking water quality. The current institutional framework in Greece is included in Circular ΔΥΓ2/Γ.Π. οικ. 111540/2010 that incorporates the Drinking Water Directive to the Greek legislation. The current legislation on monitoring quality of drinking water defines competent authorities and water managers, their responsibilities as well as their obligations. These obligations include the frequency of drinking water sampling, monitoring parameters (microbiological and physico-chemical) and the maximum parametric values (contaminants' concentration acceptable limits).

3.2. ISO 22000 and hazard analysis and critical control points

The implementation and development of an ISO 22000 system in WDSs is a particularly complex process, while at the same time it is differentiated according to the particular characteristics of each system. The development of a HACCP plan includes the identification of physical, chemical and biological hazards in the entire water supply chain, from the source to the raw water treatment plant, the storage tanks and the distribution network; the identification of critical control points (CCP), the monitoring system and corrective actions. HACCP is a systematic approach that helps water companies to identify on time potential risks and develop preventive and corrective actions aimed at preventing or reducing the consequences of the perceived risk. In recent years, several water utilities in various countries around the world have adopted HACCP systems to ensure the quality of drinking water [25]. Indicatively European countries such as Belgium, Germany, Italy, the UK, etc. have incorporated HACCP in day-to-day operations of water utilities.

3.3. Water safety plans

Water safety plans (WSPs) are tools for the systematic management of drinking water quality aiming at ensuring the safety of potable water by fulfilling the respective health objectives. WSPs are flexible and can be applied to a wide range of water utilities regardless of their size and location [26;27]. WSPs' structure is based on three pillars including system evaluation, operational control and management plans. WSPs include the system's assessment and design, operational monitoring and management plans, including documentation and communication. The elements of a WSP are built on the principles of HACCP and other systematic management approaches. These plans should address all aspects of the drinking water supply and focus on the control of abstraction, treatment and delivery of drinking water. While WSPs are used in many countries, enforceable legislation exists in Belgium, Hungary, Iceland, Switzerland and the United Kingdom (in Europe). In other countries, although they are encouraged, they are not enforced.

4. Monitoring, numerical modelling, simulation and optimization techniques in WDSs

The factors affecting the presence of undesirable elements or compounds in the water supplied through a WDS include quality, material and construction methods of pipelines and other WDS assets, the operating conditions and the frequency of technical interventions due to construction or maintenance works. Water quality fluctuates as water travels in the distribution network. Tracking concentrations and movement of pollutants in a WDS is a complex task requiring: (a) a quantity–quality hydraulic model to accurately simulate (extended period simulation) the quantity and quality of the water being supplied; and (b) the ability to monitor pollutants' concentrations in real time. Considering the mathematical model of water quantity and quality simulation, real-time monitoring and the optimal distribution of monitoring stations, it is evident that the water quality monitoring capability in WDSs is extremely important. However, there are no formal guidelines or procedures on how and where water quality monitoring stations should be installed to ensure security, given the unstable hydraulic conditions and water quality conditions. Spatial and time uncertainties are many and make the prediction of pollutants in quality models a challenge.

4.1. Monitoring

For the maximum protection of public health, each network node could be monitored, leading to a high respective cost to monitor the entire system. On the other hand, if it is assumed that the quality of the water supplied does not change as it flows through the pipes, only the network entry points (i.e., water tanks) should be monitored. The problem is quite complex as the risks of water quality degradation (accidental or deliberate) can theoretically occur at different points in the network (even if is assumed that pressurized pipes cannot be in some way detoured). Water supply networks are also very complex and have different operating characteristics. For example, disinfection in a water network is usually done by adding chlorine to the inlet of the network (e.g., water tanks, raw water treatment plants, etc.). At the same time, the dose of the chlorine used should be properly evaluated to provide adequate concentrations of residual chlorine throughout the network, up to its dead ends being usually far away from the chlorine input sites. However, this practice may result in higher concentrations of residual chlorine at several points in the network close to these sites and uneven distribution of residual chlorine in the network. Laboratory-based methods, used for water quality monitoring, provide results after some time and thus do not allow the operators to react on-time and protect public health in real time [28;29]. Since phenomena such as a deliberate terrorist intrusion, corrosion or THM formation, can deteriorate water quality, there is a need for on-line continuous monitoring. Thus, along with laboratory analytical techniques, sensors for on-line continuous monitoring of water quality parameters are necessary to be installed at specific points throughout the network. These sensors have the ability to directly record the variation of certain water quality parameters without requiring collecting and preparing of water samples. This allows the recording of the variance of critical water quality parameters by providing continuous field data based on which the laboratory analytical data is also controlled. Alarm systems are used in advanced continuous monitoring systems. The most sophisticated continuous monitoring systems record the variability of parameters such as pH, residual chlorine, aluminum, iron, dissolved oxygen, colour, ammonia, turbidity, total organic carbon, nitrates and flow. Real-time monitoring of quality parameters has been widely recognized as a solution to reliably record the spatial and time variation of these characteristics. Existing techniques provide the ability to record a limited number of water quality parameters and at the same time have no low sensitivity limits comparable with those of laboratory techniques. New technologies have been developed to detect pathogens in real time, such as DNA microchip arrays [30], immunologic techniques [31], microrobots [32] and a variety of tools based on the optical properties of water (e.g., refractive index measurement, Raman spectroscopy, etc.) [28]. Banna et al. [29] reviewed the emerging technologies of water quality parameters and compared water quality sensors based on eight criteria. The study revealed that new sensors have to be developed.

However real-time monitoring needs to be assessed on a case-by-case basis based on the requirements and the characteristics of each WDS that de facto is a unique case study [28]. Banna et al. [29] identified some basic characteristics of on-line monitoring systems such as low cost, fast response time, reliability, minimum maintenance requirements, long lifetime. Unfortunately, on-line continuous monitoring systems have limitations regarding their sensitivity and ability to detect low concentrations of microorganisms [20]. Due to several reasons such as suspended solids or the biofilm formation, on-line sensors may not function correctly. Extremely high sensitivity may also cause frequent false alarms. Finally, these sensors do not asses the overall quality of drinking water.

4.2. Numerical modelling and simulation

Modelling the quality of the water flowing through the pipes of a WDS is necessary due to three factors: (a) water entering a WDS comes from different sources (such as rivers, lakes, aquifers, desalination plants, etc.) of different water quality; (b) water quality alterations within the WDS due to disinfectants' reactions, growth of microorganisms, reactions with pipes' walls, etc. and (c) accidental or non-incidental events of contaminants' introduction into the water network and their transfer as the water flows through the pipelines. Thus, developing simulation algorithms to model the quality of the water in WDS is considered a must for designers, water utilities and regulatory agencies for various purposes: (1) network design; (2) real-time operation; (3) monitoring; (4) simulation of contamination incidents and (5) guidelines development for planning, operation and monitoring.

Chlorine, being a well-known disinfectant, protects water by inactivating pathogens and at the same time provides adequate residual chlorine concentrations to further protect drinking water at parts of the network far away from the chlorine injection points (e.g., dead ends). The disadvantage of the use of chlorine as water disinfectant is that it reacts with the pipes following a first-order reaction [33–37]. The factors affecting this reaction are pipe material, corrosion products, existing biofilm and accumulated sediments [33,34]. Many researchers have dealt with water quality in terms of chlorine transfer within the WDS and the development of chlorine wall decay (from the reaction of chlorine with pipes' walls) [38]. In their study, Karadirek et al. [33], reported that the first water quality model was developed by Wood in 1980 [39] while in 1985 Males et al. [40] determined the spatial alterations occurring based on the Wood's model. In the same study [33], it is reported that in 1988, Grayman et al. [41] introduced dynamic algorithms in their model. In 1993, Biswas et al. [35] developed a steady-state chlorine consumption model, being the first one addressing chlorine decay at pipes' walls together with the bulk liquid phase [33,42]. Later, Rossman et al. [37] studied further the reaction of chlorine with pipes' walls, developing a model which was incorporated in EPANET software [43], to enhance water quality simulation. The resulted software is widely used for the prediction of chlorine concentrations in WDSs. The disadvantage of the software is that it does not provide accurate results in secondary pipes and dead ends [42]. An input–output model of water quality is presented by Shang et al. [44] as a particle backtracking algorithm used in WDSs analysis. The initial version of such a model was described by Zierolf et al. [45] who presented an input–output model for chlorine concentration. This model provides "the chlorine concentration at a given pipe junction and time as a weighted average of exponentially decayed values of the concentrations at all adjacent upstream junctions" [45]. A backtracking uncertainty bounding algorithm has been developed by Vrahimis et al. [46] to calculate chlorine concentration at specific locations in WDSs, as many uncertainties are present in chlorine monitoring sensors' values. This algorithm is actually a model to detect chlorine sensor faults.

Karadirek et al. [33] developed a model combining hydraulic and chlorine modelling utilizing hydraulic and water quality monitoring data. The formation of district metered areas (DMAs) in the network (in Konyaalti, Turkey) assisted in model calibration and verification. Models to predict chlorine residuals have been developed in the past [36,47–49]. A second-order model predicting chlorine residuals has been developed by Clark and Sivaganesan [50]. Gonelas et al. [12] focused on forming DMAs in a WDS considering the operating pressure and the chlorine residual concentration as the design parameters [12], while Chondronasios et al. [13] focused on optimizing DMAs formation in a WDS considering both the water aging and the operating pressure factors. As chlorine reacts with organic compounds THMs are formatted. It is stated in the literature that compared with water quality models, few models have been developed to predict the formation of THMs in chlorinated water [51,52]. Lately some studies regarding disinfection by-products optimization techniques have been published. Radhakrishnan et al. [53] used a multi-objective optimization algorithm for modelling the formation of disinfection by-products. In this study, the optimal proportion of water from various sources, dosages of alum and dosages of chlorine in the treatment plant and in booster locations were identified. Gougoutsa et al. [54] applied a central composite design using response surface methodology for the mathematical description and optimization of disinfection by-products formation. This study revealed that the main factors affecting the formation of these by-products are chlorine dose and total organic carbon.

Dead ends in a WDS are considered as "gray" and thus problematic areas regarding WDS management. In these areas, water usually remains for quite a long time (due to low water demands) before being consumed reaching the consumers' taps (the so-called water age factor). Thus, residual chlorine concentrations in the almost standing still water tend to decrease, allowing the growth of microbial pathogens [55,56]. Abokifa et al. [42] developed a model to address this issue, as dead ends sum up to 25% or more of the total WDS infrastructure [57]. The model represents the spatial distribution of flow demands while temporal distribution is also simulated using a non-homogenous Poisson process [42]. To calibrate the model, optimization was used and Monte Carlo check was done to investigate the simulation reliability.

4.3. Optimization

Modelling water quality is very important for water utility managers as they are able to see how water quality characteristics change under several scenarios. Optimization tools can accompany water quality models at all stages such as design, operation, calibration, etc. Although optimization tools are used excessively in WDS, this paper focuses only to the ones used for the scheduling of disinfectant points/stations (boosters across the WDS) and the optimal placement of chlorine concentration monitoring sensors. Disinfection practices need to improve water quality within the WDSs, applying more effective tools. The use of booster disinfection stations (in-line chlorination) provides savings in chlorine mass applied and at the same time enhance the uniform distribution of the disinfectant at consumer demand nodes.

Many studies exist on optimization of WDSs operation since 1970, with emphasis on pumps' operation (high costs which in several cases are the biggest part of the water utility's total costs) and water quality. Optimization techniques used for water quality purposes along the whole WDS and not only in the water treatment plant are found in the literature since 1990 [58,59]. As the present paper focuses on water quality, only literature on optimization techniques used for water quality are reviewed. Mala-Jetmarova et al. [59] studied water quality optimization techniques and reviewed the literature in 2017. From the studies published, it is found that the first optimization techniques were based on deterministic methods such as linear programming, non-linear programming, dynamic programming and hierarchical control methods [59]. Genetic and other metaheuristic algorithms are found in the literature used for the optimization of water quality characteristics (such as chlorine concentrations) and water age [59] and some studies present such methods linked to simulation models (e.g., EPANET) [60,61]. To achieve optimal solutions in real time, researchers used artificial neural networks [52], interpretive structural models [62] or skeletonized models [63]. The models developed used different cost functions. Some of them considered the number and location of booster stations for in-line chlorination and were minimizing the cost of the disinfectant mass dose [64–67]. Others were minimizing the disinfectant concentration deviations at customer demand nodes from desired values [68–71]. There are studies [72,73] combining the above. The literature revealed that chlorine concentrations and water age have been modelled [74,75] and optimization methods are used in combination. These models are based on different techniques such as linear programming and mixed integer non-linear programming [62,64,70], metaheuristic algorithms linked to simulation [60,61], artificial neural networks and interpretive structural modelling [62,76].

The optimal placement of sensors for detecting contaminants is also a problem addressed by a significant number of studies. Different methods applied are found in the literature: non-model-based methods using the topology of the WDS; methods based only on hydraulic simulation [77–80] and methods based on both hydraulic and water quality simulation [81–83]. The objective function requires the minimization of the non-coverage area, the number of sensors, the detection time, etc. [84]. Indicative sensor placement optimization tools include optiMQ-S and TEVASPOT combined with CANARY (events detector) [28].

4.4. Early warning systems

Early detection of water quality problems arising from accidents or malicious actions or caused during the operation of WDSs can be achieved combining various tools like real-time continuous and on-line monitoring of water quality parameters in the network; modelling and simulating of the network's performance in terms of the quality of the water supplied, combined with the hydraulic characteristics of the WDS; and optimization tools used for the optimal placement of monitoring stations, and disinfection boosters. To predict the impact of any water quality degradation event, the water quality parameters should be linked to the quality model. Water quality simulation models can be also used to check what-if scenarios. The objective of an EWS is to assist the water manager to reliably and on-time recognize the contamination events (accidental or deliberate) in the water source or the WDS and offer him the time he needs to effectively act in order to reduce or avoid backfire effects that may be caused by such an event. Although EWSs have already been developed at different areas, an EWS including real-time monitoring [29], water quality modeling and optimization is necessary to provide an integrated tool towards the achievement of water security. Risk assessment tools can indicate areas or parts of the WDS with high vulnerability. Such cases are WDS areas where critical infrastructure is directly exposed or easily accessible or where adequate monitoring can provide time for effective reaction by the water manager [16]. EWSs not only can act as protection tools in such sensitive and vulnerable water systems, but also can prevent from any possible contamination event. To integrate such EWSs, smart and integrated response strategies at all levels should be also developed [16].

5. Conclusions

Water is the source for life and its security is of paramount importance. As WDSs are complex systems and drinking water quality is affected by many factors, it is quite a challenge to safeguard drinking water security. EWSs are necessary, as they assist water managers identify contamination events early enough to permit effective responses. An EWS should consist of monitoring and modelling tools in cooperation with optimization techniques. The current paper attempted to perform a review regarding on-line continuous monitoring systems, drinking water quality modelling and optimization techniques used in WDSs. The paper does not cover all areas. On-line continuous monitoring is used to monitor water quality characteristics allowing the on-time detection of possible contamination incidents. However, limitations regarding the sensitivity and the ability to detect low concentrations of microorganisms along with operational factors such as the existence of suspended solids or the biofilm formation may exist and affect the sensors' functionality/efficiency. Water quality models have been developed to simulate chlorine transfer and concentration and to predict chlorine residuals, while only a few models have been developed to predict THMs formation. The optimization problem in WDSs has been addressed since the 1970s developing models based on deterministic methods at the beginning and then on artificial neural networks to achieve optimal solutions in real time. Metaheuristics algorithms linked to simulation are also used. These models are mainly used to identify the optimal placement of booster disinfection stations and monitoring sensors. "Simheuristics", an approach utilizing a simulation model of a problem with metaheuristics, allows model developers to deal with real-life uncertainty in a natural way, by integrating simulation into a metaheuristic-driven framework [85]. Current research for WDSs lacks the "Simheuristics" implementation, although they are used in other applications. Usually only heuristic or metaheuristic methods are employed, and results are verified via simulation. The "simheuristic" approach can be used for connecting the metaheuristic optimization with the simulation performed by hydraulic simulation software. Combining "simheuristics" with simulation tools can evaluate each solution generated from the optimization model on every step and provide the input for generating the next candidate population. This approach will lead to a more robust solution, which will utilize the latest advances in software and hardware fields. "Simheuristics" are not widely used in hydraulic and water quality problems in WDS. An integrated approach is needed for the effective and efficient water quality management in WDSs. This approach will comprise of technical tools such as EWSs described in this paper along with proactive risk management methods (HACCP or WSPs). In this way, advanced tools will be used during the operation of the WDSs and at the same time smart and integrated response strategies will be developed to deal with any possible threat.

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