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Water Quality Assessment and Design of Cholorine Disinfectant System

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ABSTRACT: Disinfection of water is a crucial step in the treatment of water in order to obtain clean drinking water. The use of water disinfection as a public health measure reduces the spread of diseases. This research paper examines water quality assessment of ground and surface water samples obtained from lkole campus of the Federal University Oye-Ekiti (FUOYE). The obtained stream water was tagged Sample A, and the ground water (borehole) was tagged Sample B. These two constitute major source of water in the campus. Initial water quality assessment of the parameters that effect chlorine decay was done and compared with World Health Organization (WHO) and Nigeria Standard for Drinking Water Quality (NSDWQ) standard for chlorination. Examples of such parameter includes: temperature, pH, turbidity, coliform count etc.

KEYWORDS: drinking water; sterilization; sterilization by-products; early warning system

I. INTRODUCTION

Water is the essential component for life and therefore its safety is of paramount importance. Drinking water is supplied to water consumers through water distribution networks system (WDNs), being complicated civil infrastructures, comprised of hundreds of kilometers of pipes, storage tanks, pumps, valves and other important assets for the operation of the WDN. It is easily understandable that water quality changes as water is travelling through WDNs. In fact, water quality deteriorates compared to the quality of the water coming out of the water treatment plant or found at the initial parts of the network. Except of chemical compounds found in water, there is an important microbial load which might cause adverse effects to human health. Microbial load exists in natural water coming from surface or groundwater sources. Additionally, there are several potential hazards for water safety, due to normal operating conditions, natural disasters and malicious threats [1]. Natural disasters such as extreme weather phenomena (floods) or earthquakes might cause several damages to WDNs and may result in the entrance of micro-organisms at several parts of the network. Malicious threats might include terrorism attacks using biological or chemical compounds that may cause adverse effects to the health of water consumers. Even under normal operating conditions it is possible that contaminants might enter the network, after a scheduled or not, maintenance or even during normal operations (e.g., due to leaking pipes allowing substances from the ground to enter in the network) [1]. As sometimes sewerage networks are located above water supply pipes, possible leakages in both networks might be the cause for water contamination. Other potential cases where water safety is threatened by normal operating conditions, is when techniques such as pressure management are applied by the water utilities to reduce water losses. Reducing the pressure, water age (being the time water remains within the network) increases, especially at dead-ends of the network. Increased water age means that water quality is deteriorated [1

II. STERILIZATION PROCESSES

Sterilization is a crucial water treatment method as it ensures that water is free of pathogenic micro-organisms causing water borne diseases. It is worth noting that in the U.S. cholera incidence was reduced by 90%, typhoid by 80% and amoebic dysentery by 50% after introducing sterilization in water treatment [2,3].

It is known that sterilization is affected by many parameters such as water temperature, water pH, type of existing bacteria, type of sterilization, disinfectant dose, contact time and inorganic and organic material existing in water. Although sterilization is the method for the removal (or inactivation) of pathogens, sterilization itself can result in the formation of inorganic and organic sterilization by-products (DBPs). DBPs are usually trihalomethanes (THMs) and halo acetic acids (HAAs).

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There are many methods used for sterilization purposes. Chlorination is the most widely used sterilization method, where liquefied chlorine gas or sodium hypochlorite solution (sometimes the term "chlorine" is used) is added in water [4]. Alternatively, chlorination is used. This process involves the formation of monochloramine from ammonia and chlorine dosed in water. Chlorination requires a good process control as there are implications in taste and the formation of by-products (Table 1). Comparing the capability to ensure water without pathogens, chlorine is better than monochloramine, as chlorine is capable of maintaining a residual in distribution, able to react with other pathogens met in the distribution network. However, while chlorination may result in the formation of trihalomethanes (THMs), chlorination does not form THMs [4] (Table 1).

Chlorine dioxide is also used for sterilization purposes. Although it is more powerful than chlorine and does not form THMs when reacting with humic substances, chlorine dioxide is generated on demand and it is substantially more expensive (Table 1).

Another chemical sterilization method is the use of ozone, a powerful disinfectant able to inactivate *Giardia* or *Cryptosporidium*, not inactivated easily with other methods. The use of ozone however has high capital and operating costs (Table 1) [4].

Other chemical disinfectants include copper silver ionization and hydrogen peroxide [4]. However, it is not scientifically verified that copper silver ionization is an effective disinfectant. Hydrogen peroxide is not used for drinking water sterilization as it is unstable in storage and its effectiveness in bacteria and viruses is questioned.

Non-chemical sterilization technology is the use of UV radiation which is an effective disinfectant and can be used to sites limited in space.

The sterilization processes and their key advantages and limitations are given in Table 1 [4].

III. STERILIZATION EFFECTS

One of the major concerns about sterilization processes is the formation of by-products that can be dangerous for the human health. DBPs are formed due to the disinfectant overdose or inappropriate use. Organic and inorganic compounds react with the disinfectant and form by-products, organochlorine ones and inorganic ones. Organic compounds include trihalomethane (THM) and halo acetic acids (HAAs). The first researches on DBPs appeared in the 1970s, when Rook

and others identified chloroform and other THMs in drinking water [2,5,6]. The formation of these DBPs is related to the existence of organic matter in water, water pH and temperature and the type of disinfectant used. Except of organic by-products, inorganic by-products are also formed such as chlorate and bromate related to the type of disinfectant. The problem is even bigger as DBPs are formed along the water distribution network depending on the retention time in storage tanks and pipelines, as well as the disinfectant dose being able to maintain a residual along the distribution network (and especially its dead-ends). Regarding chlorination, chlorine residual is considered as the most accepted and reliable indicator for real time control of bacteria. Research has not revealed any micro-organism that meets all criteria to become a reliable indicator for sterilization efficacy.

DBPs may have adverse effects on human health. Extended research on the topic showed that DBPs are blamed for cancer and reproductive/developmental effects [2]. Sadiq and Rodriguez [7] reported on the THMs effects in human health, impacting negatively to human organs such as liver, kidney and the nervous system, have negative reproductive effects and potentially cause cancer [7]. 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 [8]. 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 [8].

Although it is believed that only surface waters, due to their organic load, react with disinfectants forming DBPs, they can also be formed in groundwaters where anthropogenic contaminants are found. More than 600 DBPs are reported in the literature [2,9]. Some of the DBPs are regulated and others are considered as emerging DBPs as they have lower occurrence levels and toxicological effects [2]. Richardson et al. [2] studied the quantitative occurrence and the health effects of 85 DBPs concluding that drinking water is a complex mixture and thus there are synergistic effects. People are exposed not only to water through drinking but also through other activities such as bathing, cleaning, washing (dermal and inhalation exposure) etc. Additionally, studying the effects of individual DBPs does not reveal the actual situation as groups of DBPs exist in water at different concentrations, having different synergistic effects. THMs include chloroform, bromodichloro methane, dibromochloro methane, and bromoform [2].

Regulations or guidelines to control DBPs and minimize consumers' exposure to potentially hazardous chemicals maintaining adequate sterilization are set by many organizations, such as U.S. EPA, the World Health Organization (WHO) and the European Union. U.S. EPA has set 100 mg/L as the maximum contaminant level for total THMs (total

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concentration of four THMs), while WHO guidelines set chloroform concentration to 0.2 mg/L, chlorodibromomethane and bromoform to 0.1 mg/L each and bromodichloromethane concentration 0.06 mg/L. European Union guidelines set total THMs concentration to 0.1 mg/L. Even the new guidelines that will be included in the updated drinking water directive set the same value of total THMs but encourage water utilities to pursue lower concentrations without affecting sterilization. Many water utilities trying to comply with the new regulations changed their sterilization practices using other disinfectants such as ozone, chlorine dioxide or chloramines in primary treatment and chlorine as a secondary disinfectant.

However, the alterations in disinfectant methods may raise new issues and problems. In Greece the maximum acceptable level of total THMs is set by the Joint Ministerial Decision (Y2/2600/2001) to
0.1 mg/L, complying with the EU Drinking Water Directive 98/83/EC.

To evaluate the risk posed by multiple contaminants in water, the Relative Health Indicator (RHI) was developed by Seidel et al. [10]. RHI is a semi-quantitative indicator that takes into consideration both cancer and non-cancer health outcomes from the exposure of various contaminants (chemical and microbial) found in water. DBPs are listed as one of the top ten risks at national level in the U.S. [10].

IV. PREDICTIVE MODELS

DBP concentrations differ at the storage tanks and within the water distribution network (WDNs) and especially in their dead-ends. Reaction time is the key factor, as longer reaction time leads to higher consumption of residual disinfectant and results in more formation of DBPs [11,12].

Chen and Weasel [1] and Rossman et al. [13] showed that HAAs degrade in WDN's dead-ends. pH and temperature are proportional to THMs formation, but pH effects vary for different DBPs [7].

Many predictive models have been developed for the DBPs formation. Sadiq and Rodriguez [7] reviewed models based on laboratory studies and/or real field data. The first models for chlorinated DBPs appeared in 1983 [14] predicting the formation of total THMs, while the first models for other DBPs appeared in 1994 [15]. Many models followed, some of them based on laboratory data and others on field data. Field studies compared to laboratory ones take into consideration the effects of the distribution system on residual disinfectant concentration and DBP formation as they measure or observe human exposure [7]. Another difference is the contact time, that can be easily estimated in laboratory studies, needs tracer studies or hydraulic simulation models in field studies. Prediction models are based on empirical relationships or kinetics involved during chlorination.

DBPs formation depends on the water quality and several operational parameters related to sterilization. It is accepted that DBPs formation varies from one place to the other. The developed predictive models are based on many parameters such as temperature, pH, reaction time, dissolved organic carbon, chlorine dose, initial residual chlorine etc. The study of Sadiq and Rodriguez [7] presents the predictive models developed and their parameters (Table 2). Several studies showed that DBPs formation is proportional to temperature. Micro-organisms increase as temperature increases, thus higher disinfectant dose is applied during the summer period, resulting in high DBPs concentrations. The conditions affecting the sterilization efficiency and the requirements to maintain disinfectant residuals simultaneously affect DBPs formation (vicious cycle). Several studies [16] showed that THMs concentrations are higher within the WDN compared to the storage tank. This is also due to the existence of organic matter in the biofilms located in the water pipes walls. Organic matter in water is another parameter affecting proportionally DBPs formation.

Predictive models are very helpful to the water utility managers, as they can help them during decision making, for example setting disinfectant dose, the contact time, adjustment of pH, etc. in order to reduce the DBPs formation and at the same time maintain the required disinfectant residual. These models can be also used to identify the locations for boosters in order to maintain the required levels of disinfectant residuals and reducing the DBPs formation. Water sampling points can be identified for water quality control using such models. This is why modelling and optimization tools are very helpful.

V. OPTIMIZATION MODELS

Research studies developed optimization models to maintain the residual chlorine concentrations within the specified range, minimizing the chlorine dose at the same injection points
[17,18]. Obstfeld and Salomon's [19] studied the optimization of pumps operation and re-chlorination injection points using also a WDN simulation model, minimizing the cost of construction and operation. In 2004, Prasad et al. [20] developed an optimization model for the injection boosters' location and their programmed, minimizing the total sterilization dose and maximizing the volume of supplied water.

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Optimization models have been developed related to the formation of DBPs. Specifically, one of the optimization models developed for DBPs formation is the one of Radhakrishnan et al. [21]. They used a multi-objective optimization algorithm to optimize the proportion of water from various sources, dosages of alum, and dosages of chlorine in the treatment plant and in booster locations. The study of Gougoutsa et al. [22] applied a central composite design (CCD) using response surface methodology (RSM) for the mathematical description and optimization of DBPs formation. This study revealed that the main factors affecting the formation of these by-products are chlorine dose and total organic carbon. A Water Quality Index is proposed by Islam et al. [23] to maintain the required residual chlorine level, using combined microbial, chemical and aesthetic quality. This study identified the optimal re-chlorination injection points and amounts. Regarding DBPs, several studies tried to minimize the operational and capital cost of the injection boosters [24], using also hydraulic simulation models [25,26]. Other studies [27] tried to optimize the booster locations and the disinfectant doses allowing for proper residual chlorine in present and future conditions.

VI. DISCUSSION AND CONCLUSIONS

It is generally accepted that sterilization is crucial for the supply of safe water to the consumers. However due to the DBPs formation, it may cause adverse effects to human health. Modelling and optimization tools have been developed and can be found in the literature. Safe water supply should meet all quality standards at all times during water distribution, up to the consumers' tap. What is of crucial importance is to detect in real time potential water quality problems and avoid them. There are two ways to do that: (a) apply risk management systems and (b) use early warning systems for water safety. These ways are not alternative ones but should be used in parallel. Risk management systems can identify all potential risks and design measures to manage these risks. The risk-based approach has several benefits, such as:

- Prevention is considered of primary importance through good management practices, instead of testing the treated water, where corrective actions have limited effects;
- It is a systematic approach that manages water quality in the whole water cycle, from the water intake points to the consumers' taps;
- It is a method that provides transparency to the consumers and they can trust the water supply.

Risk-based approach uses tools such as HACCP (Hazard Analysis and Critical Control Points) and Water Safety Plans [28]. Such tools can indicate parts of the WDN highly vulnerable to certain risks.

Early warning systems are identified as important tools for water safety. The methods applied so far can identify potential hazards in water supply, but they do not do that on time. The late identification of any hazard can potentially have serious implications to the economic life and the human health. Early warning systems should include an integrated methodology using online monitoring tools, water quality modelling and optimization tools. Early warning systems can act as protection tools and prevent for potential contamination incidents.

Online monitoring cannot replace the traditional sampling and laboratory-based analytical techniques which are very crucial for water quality monitoring, but it can provide ex ante water quality assessment indicating potential water contamination. Online monitoring 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 [1]. Although research is advanced in online monitoring tools there are still some issues to be tackled. For example, monitoring tools are not very sensitive and do not have the ability to detect low concentration of micro-organisms and in any case, they cannot replace traditional water sampling and analytical control methods. The proper functioning of such sensors depends on several causes such as biofilm formation, suspended solids, etc. and sometimes false alarms are caused.

Modelling tools in cooperation with optimization tools ("simheuristics") are able to provide robust solutions by checking the impacts of each optimization solution using mathematical modelling and simulation. The cooperation of these tools will be able to provide the optimal solutions for water sampling and also the optimal locations for sterilization boosters (inline) and their optimal disinfectant dose. The authors are currently working on the development of a model for the prediction of THM formation in Greek water utilities.

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