Environmental Engineering and Management Journal

August 2020, Vol. 19, No. 8, 1309-1316
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

ANALYSIS OF THE EFFICIENCY OF WATER TREATMENT PROCESS WITH CHLORINE

Alice Iordache, Alexandru Woinaroschy*

Department of Chemical and Biochemical Engineering, University POLITEHNICA of Bucharest, Romania

Abstract

The quality of drinking water can be kept under control through the protection of raw water sources and the permanent monitoring and control of the processes of treatment and distribution of drinking water. The dangers and risks faced by drinking water supply systems may arise from inside or outside the system. Water disinfection is the key element behind obtaining and maintaining quality. Chlorine is the most widely used disinfectant, due to its high efficiency. However, it has a major disadvantage, namely that it has a fairly fast decomposition power in the distribution network. The study highlights the need for the presence of free residual chlorine in drinking water, both at the exit of the treatment station (Palas Constanța water treatment complex) and at the end of the network (Eforie Nord network) by monitoring the two points, in the period January 2013 - December 2018. The presence of free residual chlorine in the drinking water at the parameters imposed by the legislation in force ensures a protection of the microbiological quality of the water. Monitoring the quality indicators of drinking water is an essential step to prevent the risk of disease of the population. The purpose of the study is to determine the potential relationship between the presence of free residual chlorine and microorganisms in the distribution network and risk factors.

Key words: chlorination, disinfection, monitoring, risk, quality

Received: November, 2019; Revised final: February, 2020; Accepted: April, 2020; Published in final edited form: August, 2020

1. Introduction

Drinking water supply is essential for the health of users, quality of life, economic activity and sustainable development. Thus, it is imperative to ensure the continuous improvement of all the processes and treatment steps that lead to ensuring the quality and safety of the water (Gwenzi et al., 2015; Roeger and Tavares, 2018). The requirements of drinking water are increased in relation to the availability of water resources, and the quality of the raw water (groundwater and surface water) used for drinking water is not always in accordance with the legal regulations in force (Lucaciu et al., 2011).

Identifying the dangers and potential risks both to the water source and to the water treatment and distribution system, increasing concerns about public health and the environment contribute to recent positive developments in the water sector in many countries (Roeger and Tavares, 2018). Risk assessment involves analyzing the likelihood of the occurrence of risks and the impact of the potential consequences of the occurrence of the risks (Moldovan, 2018). Depending on the risk assessment identified in the water supply system, the risk management elements are established (Sandu and Racovițeanu, 2002). It must be borne in mind that it is not sufficient to assess the consequences and to keep them under control, but it is necessary to eliminate or control the causes of the occurrences of risks.

Until the beginning of the 20th century, the quality of the drinking water was evaluated by its organoleptic characteristics. Since the twentieth century, due to insufficient data and the lack of confidence in this assessment, parametric rules have been implemented to monitor the quality of water

* Author to whom all correspondence should be addressed: e-mail: a_woinaroschy@chim.upb.ro

intended for human consumption. Thus, technical and legislative methods have been developed to ensure water disinfection in public water supply systems. Disease control caused by microbiological contamination of water has been greatly improved.

In 1958, the World Health Organization published the first international standards specifically dedicated to the quality of drinking water. Subsequent reviews, guidelines for drinking water quality (GDWQ), were published in the 1980s: recommendations, health criteria, monitoring and control of community supplies. Their implementation has made progress in the protection of public health, offering a health risk analysis.

In the European Union, the first directive aimed at this topic was published in 1980 (Council Directive 80/778/EEC, 15 July). Subsequently, Council Directive 98/83/EEC, issued on November 3, included technical and scientific progress, emphasizing the obligation to respect water quality parameters. Directive 98/83/EEC on the quality of water intended for human consumption is a tool for controlling the quality of drinking water (Roeger and Tavares, 2018). This directive was transposed into national law by Law no. 458/2002 regarding the quality of drinking water.

The quality of drinking water can be kept under control by protecting the water sources and controlling the processes of water treatment, distribution and handling of drinking water. Problems facing water supply systems can be classified into two broad categories: outside the system (insufficient knowledge of the water supply system, ignorance of dangers and risks, natural disasters, poor communication), and inside the system (faulty operation, old or defective equipment, non-observance of the sanitary protection zones, the affected infrastructure, incorrect reagent dosing, insufficient water monitoring, corroded and aging distribution pipes) (Sandu and Racovițeanu, 2002).

The chemical processes of water disinfection are characterized by the use of bactericidal chemicals such as: chlorine, chlorine dioxide, sodium hypochlorite, ozone, ultraviolet rays. Chlorine and ozone are among the most commonly used disinfectants worldwide (Mosse and Murray, 2015).

Each of the disinfection agents has a specific spectrum of action that is variable in time and conditioned by the quality of the raw water (Farooq et al., 2008). Table 1 shows the advantages and disadvantages of using the most common disinfection agents. Chlorine is commonly used for water disinfection, due to its high efficiency and relatively low cost compared to other disinfectants. However, one of the disadvantages of chlorine is the potential for relatively rapid decomposition in the distribution system. Throughout the distribution system the quality of the water must be constantly monitored to verify the presence of free residual chlorine. Loss of chlorine residues makes the distribution system vulnerable to microbial contamination (Mosse and Murray, 2015; Farooq et al., 2008).

2. Case study

2.1. Description of the water supply system Constanța, Litoral

Galeșu Source

The Galeșu surface water source is located on the banks of the Poarta Albă - Midia Năvodari canal, Galeșu village.

Table 1. Disinfectants used in the water treatment process (Sandu and Racovițeanu, 2002)

DISINFECTION AGENT	***ADVANTAGES***	***DISADVANTAGES***
Chlorine	It is remnant (residual) in the distribution network. High microbiological efficiency of high disinfection. Low costs. High validity term (1 year).	Requires long contact time. Potential for rapid decomposition.
Sodium hypochlorite	It is remnant (residual) in the distribution network High microbiological efficiency of high disinfection. Low costs.	Requires long contact time. Potential for rapid decomposition. Short validity term (45 days).
Chlorine dioxide	It is remnant (residual) in the distribution network. They do not form trihalomethane by-products. It has good oxidizing power, oxidizes phenols and is very effective at pH over 8.5.	Requires instant preparation and dosing. At too high a dose it can form chlorates. Higher costs in relation to chlorine. It is unstable and explosive at temperatures above 40^0C.
Ozone	It has the highest oxidation capacity. Total elimination of biological, microbiological and micropollutant compounds. Eliminate pesticides.	Requires instant preparation and dosing. High energy consumption. It can form bromates or aldehydes by-products. There is no remnant (residual) in the distribution network.
Ultraviolet radiation	UV sterilization is safe and effective. It does not change the taste, smell, pH and color of the water. High microbiological efficiency of disinfection. Disinfection is done immediately (3-5 seconds).	Only effective for short water supply networks, not suitable for large systems.

The source has a catchment capacity of 13050 m^3 / h and supplies the Constanța, Eforie Nord, Eforie Sud, Năvodari, Lazu, Agigea, Cumpăna, Lumina, Oituz, through the Coastal System. The catchment of the type of "shore outlet" is made by 5 sorbets with the diameter from Dn 1000 mm OL to Dn 1200 mm OL, embedded in a concrete support wall, from the Poarta Albă channel - Midia Năvodari and transported to the Palas Constanța treatment complex. In front of each sieve are fixed metal grills with the role of holding bodies in suspension.

Cișmea I A and Cișmea I B Sources

The sources Cișmea I A and Cișmea I B are located on the left side of the road DN 2A Constanța - București, at the entrance to Constanța locality and has an area of approx. 5 ha, area constituting the area of sanitary protection of the source. Source Cișmea IA has a capacity of 1865 m^3/h and has a number of 10 wells (whose depth varies between 50 - 97 m), and Source Cișmea IB has a capacity of 1453 m3 / h and has a number of 10 wells (whose depth varies between 60 - 120 m). The water collected from the sources is pumped through the pipelines to the Palas Constanța treatment complex.

Cișmea I C Source

The source Cișmea I C is located on the right side of the road DN 2A Constanța - București, at the entrance to Constanța locality and has an area of approx. 8.8 ha, area constituting the sanitary protection area of the source. The source comprises 16 wells drilled at depths between 57 m - 90 m (with the exception of well P35 which is drilled at a depth of 300 m). The source has a capacity of 4339 m^3/h. The water collected from the source is pumped through a pipeline to the Palas Constanța treatment complex.

Cișmea II Source

The source Cișmea II is located on the left side of the road DN 2A Constanța - București, between Constanța and Ovidiu and has an area of about 5.67 ha, area constituting the sanitary protection area of the source. The source comprises 12 wells drilled at depths between 90 m - 150 m (except the P35 well which is drilled at a depth of 300 m). The source has a capacity of 1940 m^3/h. The water collected from the source is pumped through a pipeline to the Palas Constanța treatment complex.

The Palas Constanța treatment, storage, pumping complex

This complex is located in the industrial area of the city of Constanța, on Aurel Vlaicu Boulevard, Palas neighborhood, with an area of about 7.8 ha. The complex can take over the entire flow captured from the Galeșu surface source, as well as the water collected from the underground sources Cișmea I and II. The volume of water stored within the complex is repurposed in the distribution network of the city of Constanța, as well as in the Litoral water supply system. Water supply systems are considered as a series of successive steps that need to be followed and integrated to obtain safe drinking water for consumption (WHO, 2014).

In Fig. 1 is presented the flow diagram of the Palas Constanța treatment, storage, pumping complex.

The flow chart (Fig. 1) provides a graphical representation of the water treatment process. Flowcharts are used in risk analysis as a basis for assessing the presence, increase, reduction or introduction of hazards to water quality safety and must be clear, accurate and sufficiently detailed as necessary to perform hazard analysis (WHO, 2014).

The flow diagram shown in Fig. 1 includes:

- the succession and the interaction of the treatment stages
- points of entry into flux of raw materials (raw groundwater and surface water), ingredients (chlorine and coagulant solution)
- the stage where the water treatment takes place
- stages of water quality monitoring
- the final stage of water distribution

The elaboration of flow diagrams for water supply systems is a necessary element for identifying and analyzing the dangers and risk factors at each stage, from the raw water capture and to the distribution to the users of the drinking water. The distribution system through which drinking water is transported to the consumer must be safe from contamination after treatment (WHO, 2014).

2.2. Risk factors identified in the chlorine water treatment process at the Palas Constanța treatment, storage, pumping complex

There is a wide range of contamination agents that can be present in drinking water, some of which have adverse effects on users' health. Contamination agents can come from several non-compliant sources, or even from the drinking water distribution process. Understanding the nature of the risks, the sources of contamination and how they can enter the water supply system is a very important point in obtaining the quality of safe drinking water for consumption (Hartmann et al., 2018).

The cheapest and most efficient method of obtaining safe drinking water for consumption is to maintain a risk management, based on prevention, along with a proper monitoring of the functioning of the water supply system. As each stage of the water supply system may be subject to contamination, it is important to identify the risk factors, the causes of their occurrence and the security actions that need to be applied to keep them under control (Bergion et al., 2018; WHO, 2014).

Table 2 identifies the risk factors in the chlorination phase of the water, the potential causes of the occurrence of the risks and the possible control measures/ security actions that must be taken to be able to control the risks.

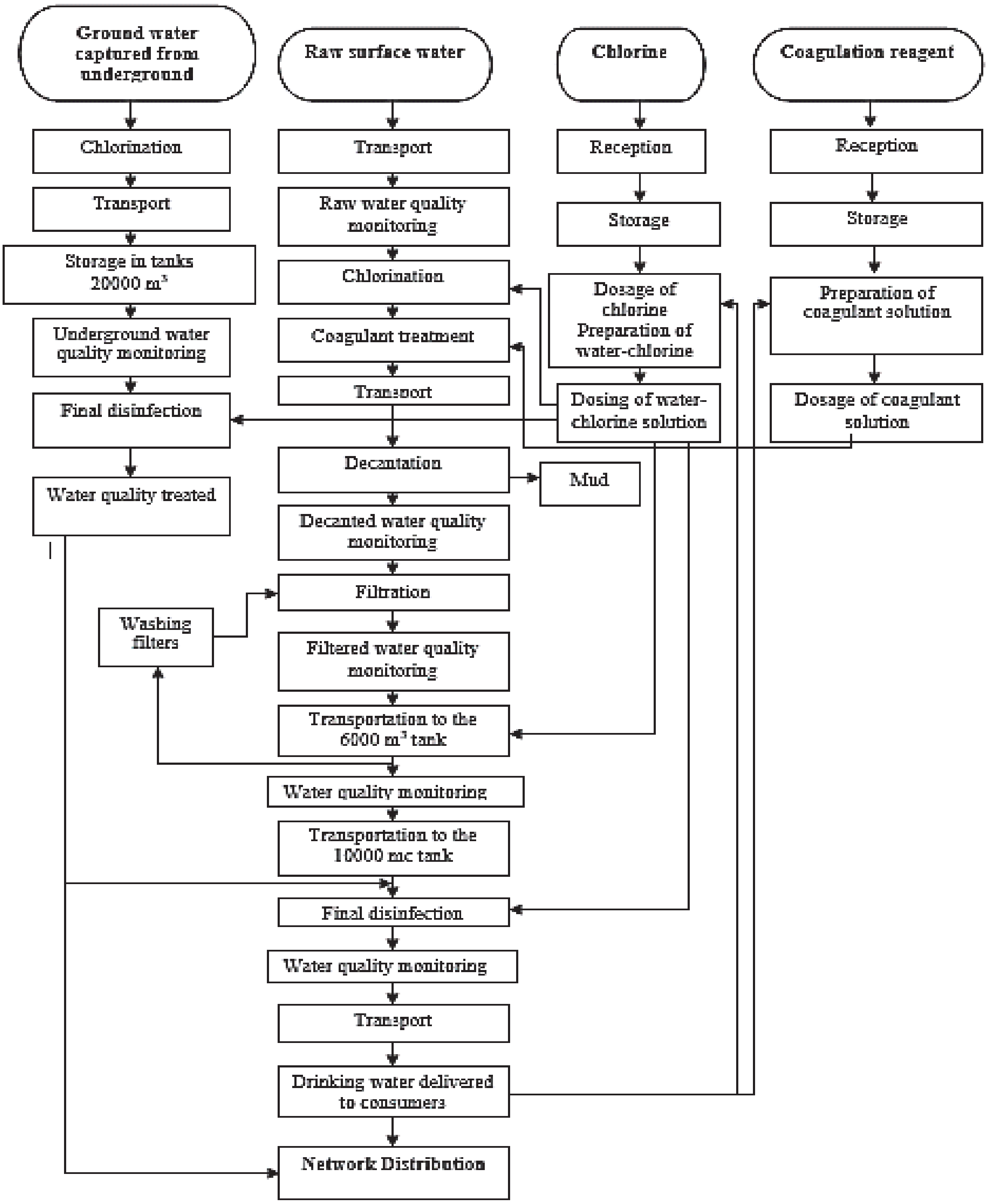

Fig. 1. Flowchart of Palas Constanța treatment, storage, pumping complex

Table 2. Identification of risk factors in the chlorination stage (Mosse and Murray, 2015)

STAGE	*RISK FACTORS*	*THE CAUSES OF RISKS*	*SAFETY MEASURES / ACTIONS*
Chlorination	- Inefficiency of water disinfection due to chlorine concentration underdose - Excess residual chlorine content due to chlorine overdose	- Insufficient staff awareness and training - Unreported defects in chlorine dosing equipment - Improper maintenance of the chlorine appliance - Failures in the distribution network and lack of washing and disinfection of the water pipe at the end of the work	- Monitoring of water quality - Compliance with the established chlorine concentration - Periodic verification of chlorine dosing equipment - Staff training and awareness - Washing and disinfecting the water pipe following a failure in the distribution network

The greatest risk involved in the chlorination activity of the water is the insufficient amount of residual chlorine for the destruction of the microorganisms in the water. In order to minimize the risks to the health of users, activities should be periodically undertaken to monitor the quality of drinking water, to verify chlorination facilities and to train staff (WHO, 2014).

2.3. Chemical and bacteriological processes taking place during water disinfection with chlorine

When the chlorine is introduced into the raw water, hypochlorous acid (HOCl) and hydrochloric acid (HCl) are formed. Hypochlorous acid (HOCl) dissociates into hydrogen ions (H +) and hypochlorite ions (ClO^-) which represent the active element.

Chlorine, introduced into the water, acts in several stages. In the first stage, the mineral substances are oxidized (salts of iron, magnesium, nitrates, nitrites etc.). In the next step, the remaining amount of chlorine acts on the ammonia (NH_4) to form chloramines (NH_2Cl, $NHCl_2$, NCl_3). They give the water a non-compliant taste and smell. Continued introduction of chlorine into water leads to the oxidation of chloramines. After this stage, an increase of free residual chlorine is recorded which is destined for disinfection (Gibbs et al., 2006; Lindhe et al., 2009). The stages of disinfection and the necessary doses of chlorine are always established on the basis of laboratory analyzes. Water samples are taken from both the treatment station, during the treatment stages, at the exit from the station and from the distribution network (Mosse and Murray, 2015; WHO, 2014).

2.4. Analysis of the effectiveness of the chlorine water treatment process

Providing continuous drinking water is a subject of international policy, as well as maintaining the quality parameters of the drinking water provided to users within the range specified by the legal requirements in force. The study on the capacity of the water treatment process for water purification consists of monitoring the free residual chlorine, coliform bacteria, *E. Coli* and *Enterococci* between 01.2013 - 12.2018 for two sampling points: at the entrance to the water supply network (the Palas Constanța water treatment complex) and towards the end of the supply network (Eforie Nord network). The legislation in force, respectively Law 458/2002 republished on 03.09.2017 regarding the quality of drinking water, specifies the limit allowed for the indicator Free residual chlorine of 0.1 - 0.5 mg / L in the distribution network (connection, end of the network), and for bacteriological indicators the allowed limit is 0. Chlorine is used to disinfect water and thus decrease, eliminate bacteriological indicators: coliform bacteria, fecal coliforms, *E. coli* etc.

During January 2013 and December 2018, a number of 576 water samples were monitored regarding the free residual chlorine, coliform bacteria, *E. Coli* and *Enterococci*. Fig. 2 shows the evolution of the free residual chlorine indicator at the departure of the Complex of treatment, storage, pumping Palas Constanța (blue) and in the network of Eforie Nord (orange).

It can be observed that in the period 2013 - 2015 the residual free chlorine indicator in the network has frequently reached the value 0, which means firstly the risk of the population's illness by increasing the values of the bacteriological indicators and secondly the non-compliance with the legal regulations in force. Fig. 3 shows the evolution of the free residual chlorine indicator from the treatment, storage, pumping complex Palas Constanța, in the network of Eforie Nord and the bacteriological indicators monitored: coliform bacteria, *E. Coli* and *Enterococci* in the network of Eforie Nord in 2013. It is noted that in June 2013, exceedances of the permissible limit concentrations of the coliform bacteria indicators, *E. Coli* and *Enterococci*, were identified due to the lack of chlorine in the water which could have caused the users to become ill.

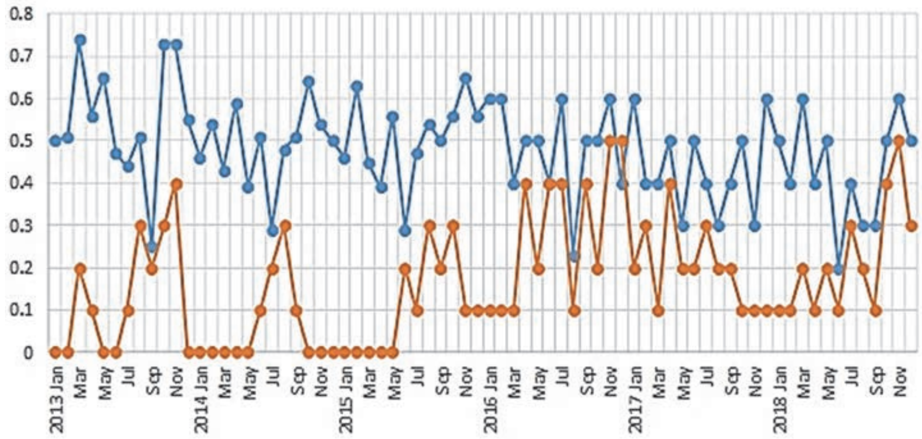

Fig. 2. Evolution of the free residual chlorine indicator in the period 2013 - 2018

The control measures should be identified both at the point where the nonconformity is detected and downstream so that their effect can be appreciated as a whole. Fig. 4 shows the evolution of the free residual chlorine indicator upon leaving the Palas Constanța treatment, storage, pumping complex, in the network of Eforie Nord, and the bacteriological indicators monitored: coliform bacteria, *E. Coli* and *Enterococci* in the network of Eforie Nord in 2014.

Also, it is noted that at the level of September 2014, there was an exceedance of the permissible limit concentrations at the *Enterococi* indicator in the network of Eforie Nord, which could have caused the users sickness. Fig. 5 shows the evolution of the free residual chlorine indicator upon leaving the Palas Constanța treatment, storage, pumping complex, in the network of Eforie Nord, and the bacteriological indicators monitored: Coliform Bacteria, *E. Coli* and Enterococci in the network of Eforie Nord in 2015.

At the level of June 2015, there was an exceedance of the allowable limit concentrations for the Coliform bacteria and *E. Coli* indicators in the network of Eforie Nord. Fig. 6 shows the evolution of the free residual chlorine indicator upon leaving the Palas Constanța treatment, storage, pumping complex, in the network of Eforie Nord, and the bacteriological indicators monitored: Coliform bacteria, *E. Coli* and *Enterococci* in the network of Eforie Nord at the level of 2016-2018. In the period 2016-2018 there were no exceedances of the bacteriological indicators.

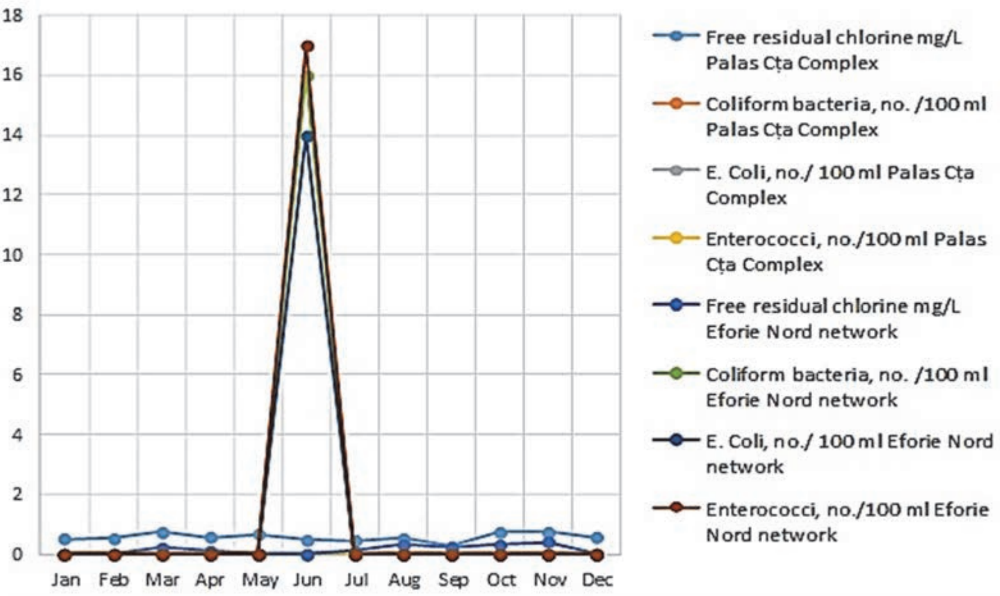

Fig. 3. Evolution of indicators of free residual chlorine, Coliform Bacteria, *E. Coli* and *Enterococci* at the level of 2013

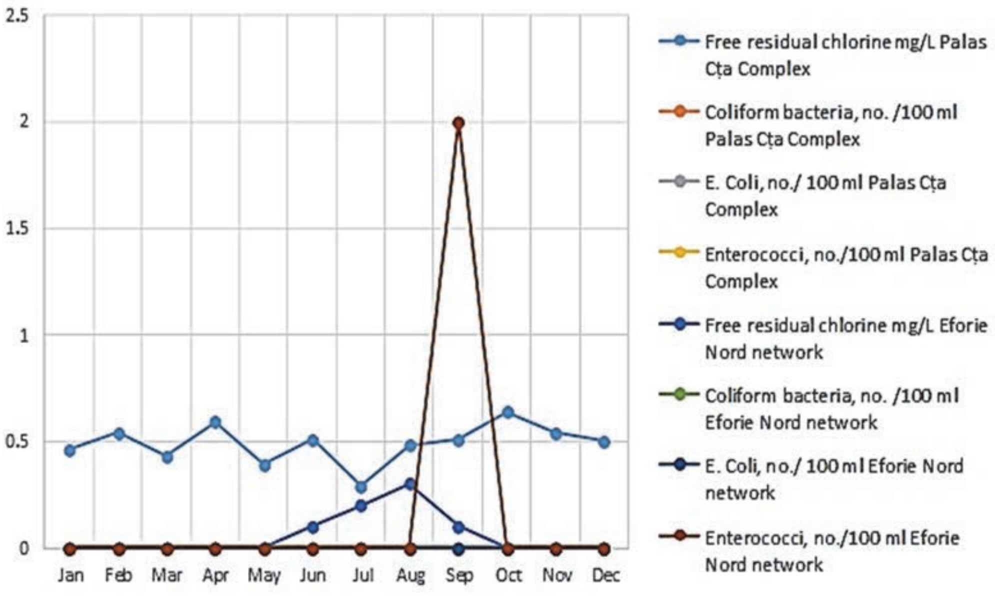

Fig. 4. Evolution of indicators of free residual chlorine, Coliform Bacteria, *E. Coli* and *Enterococci* at the level of 2014

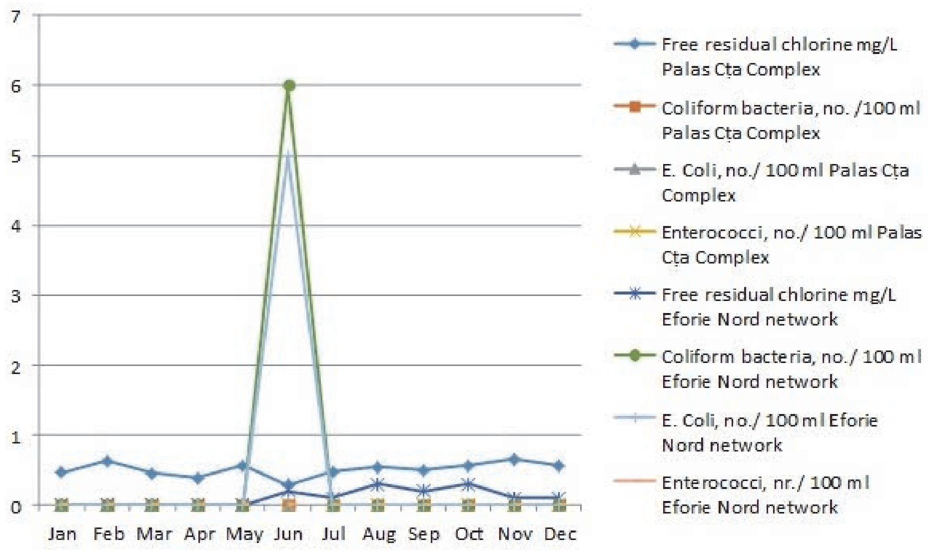

Fig. 5. Evolution of indicators of free residual chlorine, Coliform Bacteria, *E. Coli* and *Enterococci* at the level of 2015

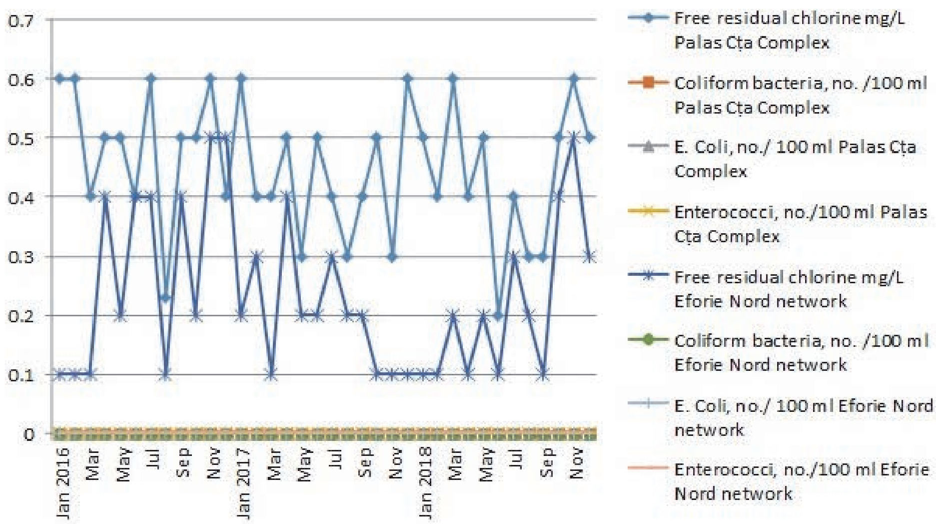

Fig. 6. Evolution of indicators of free residual chlorine, Coliform Bacteria, *E. Coli* and *Enterococci* at the level of 2016 - 2018

3. Results and discussion

The value of the free residual chlorine for the water samples taken ranged from the lowest value of 0 mg/L in the network of Eforie Nord, to the highest value of 0.74 mg/L at the exit of the Palas Constanța treatment complex. Microbiological analyzes indicated exceedances of the indicators of coliform bacteria, *E. Coli* and *Enterococci* in the years 2013-2015, mainly due to the lack of free residual chlorine in the distribution network.

As a result of the reaction of chlorine with the substances present in the water and with the deposits on the walls of the pipes, its concentration may decrease as the water passes through the distribution network. This phenomenon is known as chlorine degradation. The amount of chlorine with which the water is treated is very important.

If the dose of chlorine used is too low, residual chlorine may not remain at the end of the distribution network to protect against recontamination. If the dose of chlorine is too high, it may lead to customer complaints due to taste and odor, corrosion of the distribution network or the formation of by-products, including trihalomethanes (THM) (Gibbs et al., 2006; Hassanzadeh et al., 2016; Nescerecka et al., 2014).

As surface or ground water, used as a source for water supply systems, must meet quality conditions corresponding to the category of use, according to the legal norms and debit necessary to ensure a continuous supply, regardless of the daily, seasonal or development trends of the localities, it is necessary to follow both the indicators of potability and the operating parameters.

In order to be able to distribute safe drinking water for consumption, it is necessary that the raw water comes from a source that complies both qualitatively and quantitatively. It is much more convenient to ensure the protection of the water source and its proper maintenance than it is to be contaminated and the costs of water treatment to be much higher. In addition to the cost disadvantage, there are also the risks of chemical, bacteriological nature that lead to diseases (Gupta and Ali, 2013).

4. Conclusions

The distribution system through which drinking water is transported to the consumer must be safe against contamination after treatment. The presence of the residual disinfectant in the distribution network provides protection of the microbiological quality of the water.

During the monitored period it was possible to observe the presence of the risk of illness of the population due to the presence in the drinking water network of the Coliform bacteria, *E. Coli* and *Enterococci* indicators in concentrations that exceeded the limits allowed according to the legal regulations in force. The main factor in the occurrence of this non-compliance was the inefficiency of water disinfection due to chlorine overdose.

As possible causes may be:

- Failures of chlorine dosing devices;
- Improper maintenance of chlorine dosing devices;
- Insufficient staff awareness and training;
- Damages in the water network and lack of washing and disinfection of the water pipe at the end of the work.
- The control measures / security actions that can be taken in such situations are:
- Periodic verification of chlorine dosing devices;
- Staff training and awareness;
- Compliance with the established chlorine concentration;
- Washing the water pipe after a network failure;
- Monitoring of water quality.

Only chlorine-based disinfectants can provide residual protection. Deficiencies in the distribution system due to infrastructure degradation, network failures, make residual disinfectants even more important for the protection of public health.

An important advantage of using chlorine in the treatment of water for purification purposes is even maintaining the long-lasting chlorine residue compared to other disinfectants used. Chlorine is effective in eliminating bacteria, costs are relatively low compared to other disinfectants, and the shelf life is long (1 year).

Based on the results of this study, it is recommended to periodically monitor the concentration of free residual chlorine and the microbiological indicators at the exit of the treatment station and in the water distribution system to ensure that the chlorine residues of 0.1-0.5 mg/L are available. The minimum residual chlorine level at the end user should be at least 0.1 mg/L to ensure quality water for consumers.

References

Bergion V., Lindhe A., Sokolova E., Rosen L., (2018), Risk-based cost-benefit analysis for evaluating microbial risk mitigation in a drinking water system, *Water Research*, **132**, 111-123.

Farooq S., Hashmi I., Qazi I.A., Qaiser S., Rasheed S., (2008), Monitoring of coliforms and chlorine residual in water distribution network of Rawalpindi, Pakistan, *Environmental Monitoring Assessment*, **140**, 339-347.

Gibbs M.S., Morgan N., Maier H.R., Dandy G.C., Nixon J.B., Holmes M., (2006), Investigation into the relationship between chlorine decay and water distribution parameters using data driven methods, *Mathematical and Computer Modelling*, **44**, 485-498.

Gupta V.K., Ali I., (2013), *Environmental Water: Advances in Treatment, Remediation and Recycling*, Elsevier's Science & Technology, Amsterdam, On line at: https://www.sciencedirect.com/book/9780444593993/environmental-water.

Gwenzi W., Dunjana N., Pisa C., Tauro T., Nyamadzwo G., (2015), Water quality and public health risks associated with roof rainwater harvesting systems for potable supply: Review and perspectives, *Sustainability of Water Quality and Ecology*, **6**, 107-118.

Hartmann J., Van der Aa M., Wuijts S., Roda Husman A.M., (2018), Risk governance of potential emerging risks to drinking water quality: Analysing current practices, *Environmental Science and Policy*, **84**, 97-104.

Hassanzadeh E., Elshorbagy A., Wheater H., Gober P., (2016), A risk-based framework for water resource management under changing water availability, policy options and irrigation expansion, *Advances in Water Resources*, **94**, 291-306.

Lindhe A., Rosen L., Norberg T., Bergstedt O., (2009), Fault tree analysis for integrated and probabilistic risk analysis of drinking water systems, *Water Research*, **43,** 1641-1653.

Lucaciu I., Cruceru L., Cosma C., Nicolau M., Gheorghe S., Dinu L., Patroescu V., Hem L.J., Hafskjold L.S., Eikebrokk B, (2011), Monitoring the quality of water intended for human consumption (in Romanian), *Rom Aqua*, **75**, 26-30.

Moldovan D., (2018), Aspects regarding risk management in the process of transportation and distribution of drinking water (in Romanian), *Rom Aqua*, **125**, 42-45.

Mosse P., Murray B., (2015), *Good Practice Guide to the Operation of Drinking Water Supply Systems for the Management of Microbial Risk*, Water Research Australia Limited, Final Report, WaterRA Project 1074, On line at: https://iwa-network.org/wp-content/uploads/2019/04/Good_Practice_Guide_Operation_Drinking_Water_Research_Prj_1074.pdf.

Nescerecka A., Rubulis J., Vital M., Juhna T., Hammes F., (2014), Biological Instability in a Chlorinated Drinking Water Distribution Network, *PLOS ONE*, https://doi.org/10.1371/journal.pone.0096354

Roeger A., Tavares A.F., (2018), Water safety plans by utilities: A review of research on implementation, *Utilities Policy*, **53**, 15-24.

Sandu M., Racovițeanu G., (2002), *Handbook for Sanitary Inspection and Monitoring of Water Quality in Water Supply Systems*, (in Romanian), Conspress Publishing, Bucharest, Romania.

WHO, (2014), Water safety in distribution systems, World Health Organization Document Production Services, Geneva, Switzerland, On line at: www.who.int.