Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2020.25801

199 (2020) 331–338
September

Influence of treatment efficiency on microbiological stability of water

Izabela Zimoch[a,*], Mirosława Skrzypczak[b]

[a]*Faculty of Energy and Environmental Engineering, Institute of Water and Wastewater Engineering, Silesian University of Technology, Konarskiego 18, 44-100 Gliwice, Poland, Tel. +48 32 237 28 84; Mobile: +48 606 624 196; email: izabela.zimoch@polsl.pl (I. Zimoch)*
[b]*Silesian Waterworks PLC, Wojewodzka 19, 40-026 Katowice, Poland, Tel. +48 32 603 88 61; email: morciolmira@yahoo.com (M. Skrzypczak)*

Received 13 November 2019; Accepted 8 March 2020

ABSTRACT

The declining trend in water demand that has lasted for several dozen years now forces water and sewerage companies to undertake investment activities. These activities are aimed at the modernization of existing water-pipe networks to enhance the guarantee of maintaining the adequate water flow velocities that will ensure the stabilization of the quality of water intended for human consumption. Quite often, an oversizing of a distribution network and hence changes of operating conditions of water distribution network may lead to secondary water contamination making water harmful to human health. The problem of secondary water contamination is particularly important for water supply systems (WSS) that intake raw water from surface reservoirs. In this case, periodic algae and blue-green algae blooming is an issue pose a threat to proper water treatment processes. This article presents the results of the assessment of the effect of the water treatment process on the microbiological stability of water in the WSS, which works on highly eutrophicated surface water resources. An integral element of the analysis is the evaluation of the degree of reduction of indicator parameters in-unit water treatment processes, carried out for two variants including the period when drinking water met quality requirements as well as period of bad water quality.

Keywords: Water quality; Microbial stability of water; Treatment efficiency; Microbial exceedances

1. Introduction

The parameters of water intended for human consumption are strictly defined in the Regulation of the Ministry of Health on the quality of water intended for human consumption [1]. Under the provisions of the Act on the collective supply of water and the collective removal of wastewater, water, and sewerage companies are obliged to provide the capability to carry out the supplies of water of the required quality and under the adequate pressure [2]. Water and sewerage companies, in a vast majority, satisfy these requirements, treated water forced to a distribution subsystem meets the requirements imposed by current regulations. Highly advanced water treatment technologies make the quality of water immediately after the Water Treatment Plant's clean water tanks stable in terms of microbiology and chemistry.

The declining trend in water demand, and consequently in water distribution, which has continued for several dozen years, compels water, and sewerage companies to respond through undertaking investment processes aimed at maintaining the adequate water flow in pipelines, which will enable the stabilization of the quality of water intended for human consumption. Many times, an oversizing of a distribution network and changes in water distribution may lead to fluctuations in volumetric flow rates and, as a consequence, can cause a physicochemical and microbiological destabilization of the pipeline material, biofilm, and loose

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* Corresponding author.

Presented at the 14th Conference on Microcontaminants in Human Environment, 4–6 September 2019, Czestochowa, Poland

deposits in the distribution system, which have formed over decades and may contain components that cause adverse health and aesthetic effects.

Physical, chemical, and biological processes taking place in the pipeline cause the secondary contamination of water in the distribution system. The loss of the chemical stability of water is considered primarily in the aspect of changes in hydraulic conditions in the water-pipe network. Any significant change in the chemical composition of water seems a little probable. Instead, this is associated with the release of contaminations due to the detachment of deposits from the inner pipeline walls, caused by a sudden increase in flow velocity. Biological stability is related to the contents of substances in the water, which constitute nutritional substrates that support the growth of microorganisms in the water. Biodegradation of organic substances, mainly directly assimilated organic matter, creates conditions for the growth of heterotrophic microorganisms, which may include pathogenic organisms. It is heterotrophic micro-organisms that are substances potentially dangerous for consumer health, therefore, as the index to determine the biological stability of drinking water, BDOC (biodegradable dissolved organic carbon) is adopted, whose safe value ranges from 0.15 to 0.2 (0.3) mg C/L. In the case of water-rich in nutritional organic substances, the growth of heterophils is determined by the presence of biologically assimilable phosphorus (orthophosphates) [3–5].

Loss of microbiological stability can cause secondary pollution in the main network. This should raise our concern because the detection of microorganisms in treated water is time-consuming and their identification is difficult [6–8].

It is obvious that the primary objective in the supply of water intended for consumption is to deliver it with the best possible quality to the consumer's tap, and not only to the Water Treatment Plant's exit; however, impairment of water quality parameters does usually happen, especially in the end sections of the network [9,10].

The risk analysis of water supply systems (WSS) should take into consideration climate change. Looking into the future, one should make allowances for the risks of infection with *Norovirus* and *Cryptosporidium*, in conjunction with the forecast increase in the number of pathogens in potable water sources [11]. The selection of a technology to be used in a water treatment plant depends on the material that is to be treated with that technology. In the case of water treatment plants that operate based on surface water reservoirs, algae, and blue-green algae blooming is a frequent problem. On account of a build-up of biogenic substances, a worsening of water quality in stagnant water (e.g., in lakes) is visible, which is due to intensive biologic production. Algae-polluted water may be dangerous for human health [12,13].

The water quality decrease caused by algae blooming or the presence of cyanobacteria may lead even to the need for the water treatment plant to be periodically shut down [14].

During the operation of a water treatment plant, whose technology is not subject to drastic changes, and the distribution of water via unmaintained pipelines, quasi-stabilization of bacterial populations occurs [15,16].

The object of the undertaken investigation is a water treatment plant that surfaces water abstraction for drinking water. This water source is characterized by a high degree of eutrophication. In the case under discussion, historically, a need would arise for shutting down the plant due to the quality of treated water that, in spite of a high-efficiency water treatment technology, did not meet the Polish Regulation of the Minister of Health on the quality of water intended for human consumption. The article reports the results of the assessment of the effect of the water treatment process on the microbiological stability of water in the water main network. Microbiological stability of water was assessed based on both the analysis of the technological efficiency of organic matter reduction and the analysis of pH, oxidation-reduction potential (ORP), UV_{254}, total organic carbon (TOC), dissolved organic carbon (DOC), as well as free chlorine.

2. Material and methods

2.1. Subject of studies

The water supply system consists of 10 water treatment plants, 9 network tanks, and almost 900 km of the main water-pipe network. The water treatment plants mainly, in 87% operate on the surface water, the remaining 13% of supply is groundwater. The study subject is the separated zone supplied in water by Water Treatment Plant A (WTP_A). This WTP_A operates based on surface water coming from a dam reservoir built in the period 1935–1939, which was adapted to water supply purposes in the years 1948–1951. Current WTP_A's production capacity has been specified at a level of 50,000 m^3/d. The WTP_A was modernized in 2005 and the current water treatment system consists of the following technological processes.

- Pre-ozonation of raw water with a dose of 0.3 – max 4.0 mg O_3/L, with a contact time of 4 min. Two parallel pre-ozonation chambers are integrated with a flash mixing coagulation tank and then with a flocculation tank.
- After coagulation, the water flows through lamella clarifiers, whose purpose is to precipitate as much suspension as possible from the raw water. From the lamella clarifiers, the water flows to filters.
- Filtration on anthracite-sand double-layer rapid filters at a filtration rate of up to 5 m/h and with a filter cycle not shorter than 18 h.
- Intermediate ozonation of treated water with ozone dose from 0.3 to 1.3 mg O_3/L.
- Filtration on activated carbon beds.
- Water chlorination with a dose of sodium hypochlorite from 27 to 37 mg NaOCl/L.

After the treatment process, water is pumped to the distribution water-pipe network. The main water-pipe network is used to transport water intended for human consumption. Nearly 50% of the water-pipe network is built from steel.

The studies were carried out in the period from 17.01.2017 to 17.12.2018. Water samples for testing were taken from five sampling points at different places of the treatment process (raw water, water after pre-ozonation, filtration, intermediate ozonation, and in drinking water supplying water-pipe network). In addition, five points on the distribution network were choose to this study.

These points were located at the following distances form WTP_A: p1-6,191 m, p2-9,293 m, p3-15,666 m, p4-17,350 m, and p5-18,750 m. In water were determined the parameters such as: UV_{254} absorbance, pH, free chlorine. At five points on the water distribution network, additional microbiological parameters were determined, that is, coli group bacteria, *Escherichia coli*, microbial number at 36°C after 48 h, and microbial number at 22°C after 72 h. In the middle of the research period (10.07.2017–17.12.2018), for the assessment of microbiological stability, the measurements of next water quality parameters were introduced, that is, TOC, DOC, and ORP.

2.2. Research methodology

Surface water resources are characterized by high dynamics of the variability of water quality during the year, including high variability of the content of organic substances determining the microbiological stability of water. Thus, the inclusion of these waters for the purposes of supplying the population with drinking water requires both the removal of organic pollutants and their continuous monitoring of their quantity in water pumped into the water supply network. For the purpose of monitoring a parameter that best defines the total contents of organic compounds is the TOC. We can observe an increase of TOC in surface water and that it its concentration depends on season [17–19]. This is a parameter that enables the assessment of the total content of organic carbon in a dissolved and undissolved form. TOC content helps to assess the effectiveness of individual water treatment stages and shows the risk of the secondary contamination of water in the water main network [21]. As the literature shows, the biological stability of the main network water is improved by reducing the DOC content of treated water to a level of 1–2 mg C/L [20–22].

Table 1
Basic statistic of DOC and TOC in treated water pumped into the network in the period from 10.07.2017 to 17.12.2018

Parameter	DOC, mg C/L	TOC, mg C/L
N	39	74
Average	4.43	4.57
Standard error	0.11	0.08
Median	4.47	4.37
Mode	3.43	3.83
Standard deviation	0.67	0.67
Variance	0.44	0.44
Kurtosis	–0.41	–0.15
Slant	0.30	0.67
Minimum	3.27	3.31
Maximum	5.99	6.23

The currently applicable Polish Regulation of the Minister of Health on the quality of water intended for human consumption [1] does not define the parametric value of the TOC parameter. Appendix No. 1 of the Polish Regulation, Part C in Table 2 [1], gives the only requirement for TOC "without any abnormal changes" TOC_{WAC} (index WAC means without any abnormal changes). The World Health Organization (WHO) recommendations for the quality of drinking water indicate that the level of the TOC should not exceed 5 mg C/L. According to Mołczan [22] TOC_{WAC} content in drinking water is defined by Eq. (1) when the difference between the minimum Min_{TOC} and the maximum Max_{TOC} occurring during a year is less than 40% of the minimum TOC value:

$$\mathrm{TOC}_{\mathrm{WAC}} = \left(\mathrm{Max}_{\mathrm{TOC}} - \mathrm{Min}_{\mathrm{TOC}}\right) < 40\%\mathrm{Min}_{\mathrm{TOC}} \tag{1}$$

Furthermore, in research methodology, the value of redox is used for water stability assessment due to redox potential is an indication of the capability of oxidizers present in the water to maintain the water in a state free from microbiological contaminant. It is an operation parameter, which controls the effectiveness of the disinfection process. The higher the redox potential value is, the shorter the time of contact between *E. coli* bacteria and disinfectant is possible to inactivate pathogenic microorganisms. According to WHO recommendation, the minimum value of redox potential has been determined at a level of 650 mv; in that case, the water is deemed disinfected and microbiologically stable.

In this study, SUVA (the parameter of specific UV absorbance) was calculated. SUVA is a combination of absorbance in UV_{254} and the content of DOC into a single index, $SUVA_{254}$, which enables the quantitative measurement of aromatic substances in an organic carbon unit, as per Eq. (2):

$$\mathrm{SUVA}_{254} = \frac{\mathrm{UV}_{254}}{\mathrm{DOC}} \tag{2}$$

Table 2
Summary of characteristic statistical quantities for TOC in water pumped into the network

No.	Class limit	Center of the interval	Frequency, *f*	Cumulative frequency, cf	Relative frequency, rf	Cumulative relative frequency, crf	Average, $\bar{x}_w$	Mode, Mo	Median, Me
1	3.31–73	3.52	3.00	3.00	0.04	0.04	4.57	3.83	4.37
2	3.73–4.14	3.94	19.00	22.00	0.27	0.31			
3	4.14–4.56	4.35	18.00	40.00	0.26	0.57			
4	4.56–4.98	4.77	15.00	55.00	0.21	0.79			
5	4.98–5.4	5.19	9.00	64.00	0.13	0.91			
6	5.40–5.81	5.60	5.00	69.00	0.07	0.99			
7	5.81–6.23	6.02	1.00	70.00	0.01	1.00			

where $SUVA_{254}$ – specific UV absorbance (m^3/g C m), UV_{254} – absorbance in UV_{254} (m^{-1}), DOC – dissolved organic carbon (g C/m^3).

This index included information on the quality of organic contaminants that are present in the determination of absorbance. It is also an index, that is indicative of the reactivity of DOC and well correlates with the potential of formation of oxidation by-products. It also points out the susceptibility of DOC to removal by the coagulation method [22,23].

In the research methodology, it is assumed that microbiological stability of water is assessed based on both the analysis of the technological efficiency of organic matter removal and the analysis of pH, ORP, UV_{254}, TOC, DOC, as well as free chlorine. For this purpose, all tested water quality parameters are subjected to statistical analysis. For all statistical analyses, ToolPak in Excel 2016 was used for the calculation. This tool was used in the research methodology to determine descriptive statistics of the analyzed parameters – average, minimum, maximum value, median, mode, center of the interval, frequency, cumulative frequency, relative frequency, cumulative relative frequency, and weighted average. With the use of this package, a cumulative distribution function was appointed in order to assess the dynamics of the variability of water quality parameters determining the microbiological stability of water.

3. Results and discussion

Due to the specificity of the raw water, in the case of the WTP_A, it is of particular importance to control the organic matter content, which defines the degree of environmental pollution. Data collected during the conducted study (period from 17.01.2017 to 17.12.2018) on the TOC and DOC values indicate a significant variability of their content in the treated water during the year (Table 1). From the following histogram (Figs. 1 and 2) it can be found that the content of organic matter in the water pumped into the water network under consideration, as expressed by the parameter DOC, favors the loss of the microbiological stability of main network water. The lowest DOC value amounted to 3.27 mg C/L and the highest achieved the level of 5.99 mg C/L (average 4.43 mg C/L). Regarding the TOC concentration, its average value was 4.57 mg C/L (changes from 3.31 mg C/L to 6.23 mg C/L). The probability of exceeding the TOC content in water recommended by WHO reached the value of 0.214 Fig. 2, Table 2). Due to the occurrence of events in which the TOC in the drinking water exceeds the recommended value 5 mg C/L, study were carried out to determine the water state, defined as "without any abnormal changes" based on the Polish Regulation of the Minister of Health.

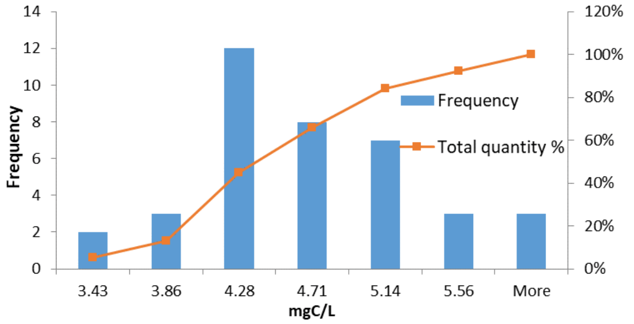

Fig. 1. DOC in water pumped into the network in the period from 10.07.2017 to 17.12.2018.

Based on the data from the period from 3.01.2017 to 04.01.2018, the values determined the level for TOC_{WAC} for drinking water from this WTP_A are presented in Table 3. It can be seen that, in this case, the effect of organic matter content makes the conditions for the growth of microorganisms in the pipe-water network favorable. Hence, it cannot be stated definitely that the drinking water pumped from WTP_A is biologically stable, that is, free from inorganic and organic nutrients [3].

The redox potential (ORP) in raw water (Fig. 3) was also determined during study. The histogram and tabular summary below (Table 4) confirm that, considering only the redox potential value, the treated water pumped from WTP_A into the network could be regarded as disinfected and microbiologically stable.

During the study, we measured additional water parameters such as: pH, UV_{254}, and free chlorine. All the values are described in Table 4.

During the study period, the $SUVA_{254}$ index for raw water was also calculated (Table 5).

The average $SUVA_{254}$ value was 2.86 m^{-3}/g C m, hence it can be inferred that coagulation, in combination with sorption methods, should prove effective up to 30% in the removal organic substances.

In the period from January 2017 to December 2018, after all, water treatment stages, the average TOC reduction level

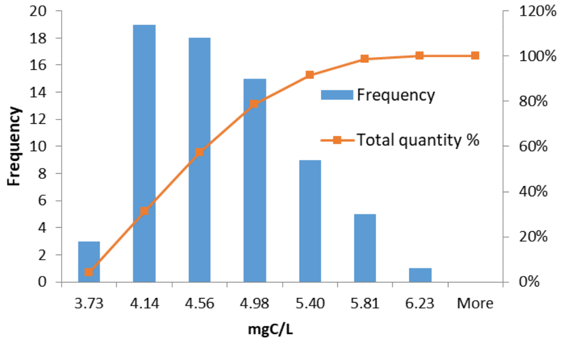

Fig. 2. TOC in water pumped into the network in the period from 17.01.2017 to 17.12.2018.

Table 3
Parameters for TOC_{WAC} of drinking water from WTP_A "without any abnormal changes" in the study period from 03.01.2017 to 04.01.2018

Min_{TOC}, mg C/L	3.29
Max_{TOC}, mg C/L	5.54
40% of Min_{TOC}, mg C/L	1.31
TOC_{WAC}, mg C/L	2.25

with respect to raw water amounted to 57%, with the highest level being 71% and 71.30% and the lowest level 44%. A process, in which the highest reduction level was noted (on average, 41%) was observed after the coagulation and filtration processes.

During the study, the effectiveness of TOC removal was determined at individual stages of water treatment, both in relation to the water from the previous, unit treatment process and in relation to raw water (Table 6). The results were compared with water samples taken at five points (p1–p5) on the main water – pipe network, where both a decrease and an increase in TOC concentration was noted between the water pumped into the network and a given point, but also between individual points. Reduction in TOC at individual water treatment stages.

According to the research methodology, the verification of the statistical hypothesis H_0 was carried out about the lack of significant statistical differences between the average concentrations for both TOC and DOC in treated water and point p4 in the water-pipe network. To verify the hypothesis, a *t*-student statistical test was used. The results of tests (Tables 7 and 8) for the adopted significance level (α = 0,05) show that there are significant statistical differences between the means in the examined data sets. Therefore, we can assume that there is an influence on TOC in treated water to TOC in the main water-pipe network, as well as the influence of DOC in treated water to DOC in drinking water in main distribution network.

The conducted study includes also a regression analysis between the TOC parameter for the treated water pumped from WTP_A into the distribution network (independent variable) and the overall number of microorganisms at 22°C after 72 h in point p4 at main water-pipe network (dependent variable). Obtained regression coefficient (*r* = 0.0433) shows weak correlation between variables.

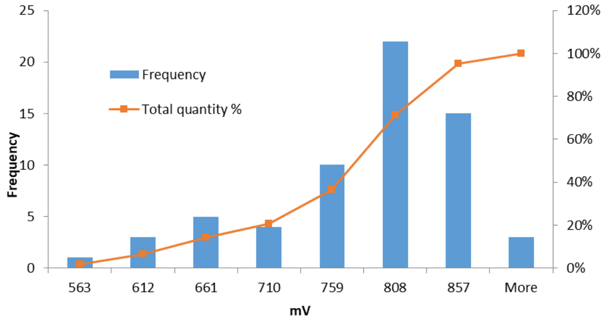

Fig. 3. Variability of redox potential in drinking water in the period from 10.07.2017 to 17.12.2018.

Nevertheless, our research indicates it is possible that the increase in the TOC in the treated water pumped into the network, which remains above 4 mg C/L, results in secondary microbiological contamination of drinking water at remote main network points situated in the same supply zone. The influence of changes of TOC, DOC as well as absorbance UV_{254} in the treated water pumped into the distribution network on the appearance of bacteria in water in consumer drinking were analyzed during a longer period from March 2016 to December 2018 (Fig. 4). Moreover, on Fig. 4, events are marked, which were recognized as a loss

Table 4
Descriptive statistics of drinking water parameters

Parameter	pH	ORP mV	UV in 254 nm (*d* = 50 mm)	TOC, mg C/L	DOC, mg C/L	Free chlorine, mg Cl/L
Average	7.53	761.36	0.18	4.59	4.41	0.58
Standard error	0.02	9.79	0.01	0.08	0.11	0.02
Median	7.57	779.50	0.17	4.52	4.45	0.60
Mode	7.62	802.00	0.15	4.74	3.43	0.64
Standard deviation	0.16	78.28	0.05	0.64	0.67	0.13
Sample variance	0.03	6,128.14	0.00	0.41	0.45	0.02
Kurtosis	–0.15	0.31	0.72	–0.27	–0.37	–0.65
Slant	–0.56	–0.84	0.96	0.34	0.36	0.02
Range	0.66	343.00	0.23	2.92	2.72	0.54
Minimum	7.16	563.00	0.11	3.31	3.27	0.31
Maximum	7.82	906.00	0.33	6.23	5.99	0.85
Sum	467.02	48,727.00	6.74	284.87	167.65	36.74
Counter	62.00	64.00	37.00	62.00	38.00	63.00
Trust level (95.0%)	0.04	19.55	0.02	0.16	0.22	0.03
Determination method	PN-EN ISO 10523:2012	PB/14 edition of 09.08.2016	PN-84/C-04572	PN-EN 1484: 1999	PN-EN 1484: 1999	PN-EN ISO 7393-2:2018-4
Measuring method	Potentiometry	Potentiometry	UV spectrometry	Infrared spectrometry	Infrared spectrometry	Calorimetry. *In situ* measurement during sample collection

Table 5
Specific absorbance index SUVA$_{254}$ in raw water in WTP_A

Date	UV$_{254}$, m^{-1}	DOC, mg C/L	SUVA$_{254}$, m^3/g C m
03.01.2017	23.02	8.90	2.58
09.05.2017	32.78	9.42	3.48
14.11.2018	27.36	11.27	2.43
12.12.2018	24.04	8.12	2.96

Table 6
Changes of reduction level of TOC during water treatment system an in water-pipe-network

	TOC redaction, %									
Parameter	Water in WTP_A					Water in water-pipe network				
	Raw water	After pre-ozonation	After filters	After intermediate ozonation	Treated water	p1	p2	p3	p4	p5
	RLp-p	RLp-p	RLp-p	RLp-p	RLp-rw	RLp-p	RLp-p	RLp-p	RLp-p	RLp-p
Average	1.41	0.23	41.41	1.45	57.02	10.09	30.97	–101.04	0.47	1.94
Max	25.05	20.42	63.82	7.79	71.30	55.29	80.20	15.92	18.79	37.01
Min	–52.38	–25.64	24.19	–4.59	43.87	–34.00	–42.24	–376.81	–18.33	–117.86
Median	3.82	–0.53	41.07	1.42	56.98	1.62	33.81	–3.40	1.20	4.29

RLp-p – reduction level in relation to previous point;
RLp-rw – reduction level in relation to raw water.

Table 7
Results of student's *t*-test with two samples of TOC for treated water and drinking water in point p4 in distribution network

Null hypothesis H_0: there are no significant differences between the means in the examined data sets		
$\alpha = 0.05$		
Statistical value	Treated water TOC, mg C/L	Water in point p4 TOC, mg C/L
Average	4.54	4.09
Variance	0.40	1.29
Observations	44.00	44.00
Pearson correlation	0.64	–
Difference of means	0.00	–
df	43.00	–
t-stat	3.34	–
P (*T* <= t) one-sided	0.01	There are significant differences between the means
Test *T* one-sided	1.68	
P (*T* <= *t*) two-sided	0.00	
T-test: two-sided	2.02	

Table 8
Results of student's *t*-test with two samples of DOC for treated water and drinking water in point p4 in distribution network

Null hypothesis H_0: there are no significant differences between the means in the examined data sets		
$\alpha = 0.05$		
Statistical value	Treated water DOC, mg C/L	Water in point p4 DOC, mg C/L
Average	4.42	3.85
Variance	0.45	1.22
Observations	36.00	36.00
Pearson correlation	0.62	–
Difference of means	0.00	–
df	35.00	–
t-stat	3.97	–
P (*T* <= *t*) one-sided	0.03	There are significant differences between the means
Test *T* one-sided	1.69	
P (*T* <= *t*) two-sided	0.00	
T-test: two-sided	2.03	

of microbiological stability, that is, the following were found in the water test sample:

- the presence of coli group bacteria, *E. coli*, *Enterococcus* group, and the bacteria of the fecal group.
- values above 100 [CFU] in 1 mL for the overall microbial number at 36°C after 48 h.
- values above 100 [CFU] in 1 mL for the overall microbial number at 22°C after 72 h.

The events are marked for five points (p1–p5) on the main water-pipe network, which are situated in the same supply zone of the WTP_A. Based on the above graph (Fig. 4), a period in the year can be determined, in which

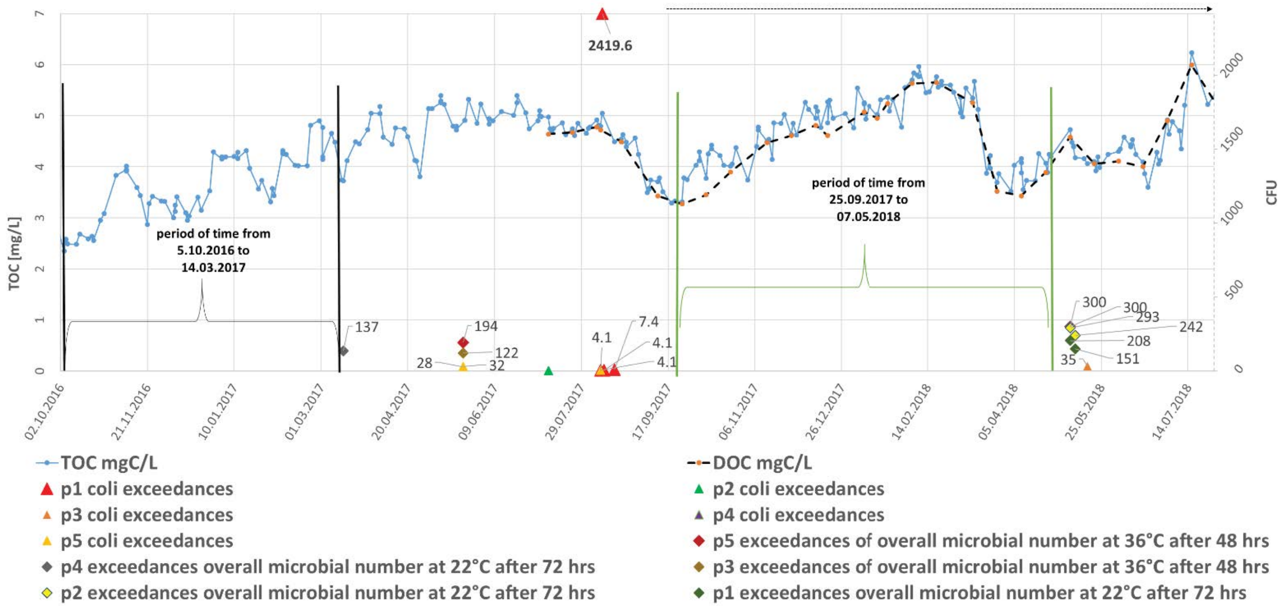

Fig. 4. Treated water pumped into the network – parameters and microbiological exceedances.

an increasing trend in TOC parameter is visible. Both in 2016/2017, as well as in 2017/2018, the increase in the concentration of organic substances resulted in microbiological exceedances, which were noted at main water distribution network.

4. Conclusions

- Notwithstanding the fact no correlations in statistical tests have been confirmed to exist between TOC values in water pumped into the network and the exceedances of microbiological parameters at points (p1–p5) located on the main network, supplied with water from the WTP_A under discussion, a strong relationship between them is visible, as has shown conducted study (Fig. 5). This is due to the fact that there is a time lag between the occurrence of the loss of biological stability of main network water and the increase in the TOC parameter. Biological stability is related to the contents of organic compounds in the water, which constitute nutritional substrates that support the growth of microorganisms in the drinking water. Biodegradation of organic substances, mainly directly assimilated organic matter, creates conditions for the growth of heterotrophic micro-organisms, which may include pathogenic organisms. It is heterotrophic micro-organisms that are substances potentially dangerous for consumer health.
- Descriptive statistics of drinking water parameters like pH, ORP, UV, TOC, DOC, and free chlorine shows that the largest percentage variability (between the maximum and minimum values) over the period considered was recorded for the UV in 254 nm (214%). The lowest percentage variability was recorded for the pH (9%).
- Conducted study indicates that an increase of TOC (about 93%) and DOC (about 72%) concentration in treated water at the beginning of the year has an effect a build-up of nutritional substances in a pipeline, which provide favorable conditions for microbial growth in spring. Our study shows that TOC variation within a year (minimum: 3.29, maximum: 5.54, and average: 4.53) in the water pumped into the network above-defined TOC_{WAC} indicates the occurrence of abnormal changes in TOC concentration (Table 3) results in losses of microbiological stability observed from May to August.
- Present research confirms the necessity to continue this investigation including additionally the analysis of the effect of main network pipeline material and the velocity of water flow at the distribution system on loss of biological stability occurred.
- In addition to the extension of studies that allow the assessment of microbiological water quality in the distribution system after the fact of bacteria occurrence in drinking water, the next study will also apply to the assessment of models to predict water quality. Those microbiological water quality models provide valuable information to decision-making and action planning.

Acknowledgments

This study was supported by the Ministry of Science and Higher Education of Poland within statutory funds – project no BK-259/RIE-4/2018 and BKM 508/RIE-4/2018.

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