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Analysis of the biological stability of tap water on the basis of risk analysis and parameters limiting the secondary growth of microorganisms in water distribution systems

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ABSTRACT

The consequence of the lack of water stability is increased susceptibility in the distribution system to secondary microbial contamination of water and thus a threat to the health of consumers. In this study, three different water quality parameters including BDOC (biodegradable dissolved organic carbon), $\sum N_{inorg}$, and PO_4^{3-} were employed to assess and evaluate the risk of loss of biostability of tap water. The analysis was based on the operating data obtained from the water treatment plant (WTP) prior to the final disinfection process for which water is supplied from intake of drilling wells, what constitute the new approach in comparison with other study. In this work, two technological schemes in the WTP were analyzed, one conventional, which is represented as WTP_c, and the other using a biologically active carbon filter (BAF), which is represented as WTP_{cf}. The modified Kaplan and Newbold method was used in determining the BDOC content by using for this purpose colonized by autochthonous bacteria bioreactor with granular activated carbon. Results show that conventional water purification processes do not provide the effective elimination of biogenic substances and, in particular, BDOC and assimilable organic carbon, therefore it is recommended to apply BAFs, as its effectiveness in removal of various impurities and the ability to stop waterborne microorganisms is very high.

Keywords: Biological stability of water; Risk; Water supply system; Water quality assessment

1. Introduction

The main task of the water supply companies is to provide the recipients with water of adequate physicochemical and microbiological quality which meets the requirements of the Drinking Water Directive (Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption) with its latest amendments including the Commission Directive (EU) 2015/1787 of 6 October 2015. The combination of unit processes used in water treatment systems should not only ensure the removal of existing pollutants to the normative values but also ensure such water quality at which there is no risk of secondary pollution during the transport in supply area [1]. The main reason for changes in the quality composition of water during transport is, apart from the technical condition of the network, the lack of biological and chemical stability of the water leaving the waterworks [2]. Bio-stable water is water without microorganisms which

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also does not sustain their development in the water supply network. The biological stability of water is, therefore, conditioned by both inorganic nutrients, that is, nitrogen and phosphorus, which are essential for the development of all forms of microorganisms, as well as the content of organic nutrients that create conditions for the growth of heterotrophic organisms (also pathogenic microorganisms) [3–6].

Based on the conducted studies, it was stated that the intensity of development of microorganisms in the water supply network is mainly determined by the presence of organic compounds, in particular biodegradable dissolved organic carbon (BDOC) and assimilable organic carbon (AOC). The values of these parameters indicate low molecular weight nutrients that can be easily assimilated by waterborne microorganisms. The AOC concentration in water entering the network is typically 0.1%–9% DOC and about 15%–25% BDOC [7,8]. Unfortunately, striving for a real reduction in the secondary bacteriological contamination of water is associated with the need for ensuring extremely low nutrient content, which is very difficult, especially in conventional purification systems [9,10].

The threshold values that restrict the secondary development of microorganisms in water distribution systems are presented in Table 1.

The concentration at which biofilm growth is inhibited depends also on the type of microorganisms, water temperature, residence time, and the type and concentration of used disinfectant [5,11].

Table 1
Threshold values that restrict the secondary development of microorganisms in distribution systems

Parameter		Value
BDOC		<0.25 mg C/L
AOC	Unchlorinated water	10–20 μg/L
	Chlorinated water	50–100 μg/L
PO_4^{3-}		0.03 mg P/L
N_{inorg}		0.2 mg N/L

BDOC, biodegradable dissolved organic carbon; AOC, assimilable organic carbon.

The data provided in Table 2 confirm that waters entering distribution systems exceed nutrient levels.

Conventional water purification processes, that is, coagulation, sedimentation, filtration and disinfection, do not ensure effective elimination of biogenic substances and, in particular, AOC and BDOC. Due to the insufficient degree of nutrient removal, it is imperative to include additional unit processes in conventional water treatment systems that will enable the removal of existing contaminants. Increasingly, biofiltration by granulated activated carbon is used for this purpose [8]. This process is characterized by high removal efficiency of dissolved organic compounds, which additionally increases after the formation of biological membrane on the surface of the deposits, thanks to that, apart from the adsorption process, there is also biodegradation [18]. The conventional water purification system eliminates AOC fraction in less than 30% and TOC (total organic carbon) in 22%, while the system with activated carbon biofiltration eliminates these fractions even to 60% and 74% [14,18].

The consequence of the lack of biological stability of water introduced into the distribution system is the development of biofilm on the internal surfaces of water pipes, the deterioration of organoleptic properties of water, that is, taste and odour and secondary bacterial contamination, including pathogenic and drug-resistant bacteria [19].

The epidemiological risk caused by the presence of biological membrane in the water supply network is related both to the quality and type of water collected by the water treatment plants (WTPs) and to the efficiency of the treatment and disinfection processes. The few pathogens present in the water can be retained on the developed biofilm, making biofilm a potential source of microbial contamination of water. This is already the case for single pathogenic cells, that is, the level of lack of detection in water samples [20–22]. The purpose of the study was to determine the influence of the biofiltration process on the risk of biological instability of tap water. The aim of this work is to investigate the effectiveness of water treatment methods in terms of the biological stability of tap water. In this work, two technological schemes in the WTP were analyzed, one conventional, which is represented as WTP_c, and the other using a biologically active carbon filter (BAF), which is represented as WTP_{cf}.

Table 2
Concentration of AOC and BDOC in tap water of various distribution systems

	Minimum concentration of providing growth	Concentration of DOC and BDOC	Literature
AOC (unchlorinated water)	10–20 μg/L	2–311 μg/L	[12]
		4–130 μg/L	[13]
AOC (chlorinated water)	50–100 μg/L	92–482 μg/L	[14]
		36–446 μg/L	[15]
		60 i 174 μg/L average values in summer and winter	[16]
		18–214 μg/L on average 94 μg/L	[17]
BDOC	>0.25 mg/L	0.03–1.03 mg/L on average 0.32 mg/L	[17]
		0.15 mg/L w 20°C, 0.30 mg/L w 30°C	[17]
		0.25 mg/L	[18]

BDOC, biodegradable dissolved organic carbon; AOC, assimilable organic carbon.

2. Materials and methods

2.1. Characteristics of the research object

The analysis concerns the system of the underground WTP for a city of about 80,000 inhabitants, the water intake devices are the two pumping intakes: the first consisting of 5 drilling wells with capacity of Q_{emax} = 183 m^3/h and the other one consisting of 22 drilling wells with capacity of Q_{emax} = 715 m^3/h. The water treatment station is powered from a quaternary aquifer with a free mirror from a depth of about 15 m ppt. The designed maximum capacity of the WTP is 715 m^3/h. The treated water flows from a clean water tank to two water mains by means of three pumps. Two of the pumps have a capacity of 440 m^3/h and a third one has a capacity of 280 m^3/h. Their lifting capacity is 58 m.

The city's water supply network consists of 17 km of mains and 177 km length of distribution network. The water household connections network consists of 3,958 connections and has a length of 99 km.

The largest percentage, about 43% of the entire water supply network, consists of pipes that are less than 20 years old but more than 11 years old. 90.2 km of network is made of materials less than 10 years old, which represents 31% of the entire water supply network. The material structure of water network is as follows: grey cast iron (38%), polyvinyl chloride (25%), galvanized steel (20%) and polyethylene (18%).

Physicochemical composition of water collected from water intake and directed to the treatment station widely varies, since it depends on the wells included in the operation and their performance. The water collected does not meet sanitary requirements in terms of turbidity, colour, permanganate index, ammonium, iron and manganese. High water colour, correlating with the excess value of the permanganate index and general organic carbon, indicates the presence of natural organic matter in water that can occur in complex combinations with iron and manganese compounds. In the examined water, there are large quantities of iron, which are rarely found in the municipal intakes. Due to the general hardness, water is classified as medium hard water and about half of that hardness is carbonate hardness. The raw water also has a high sulfate concentration. The physicochemical composition of the collected water indicates that there may be difficulties in its treatment.

Water from intake is directed to the collecting well (retention time 2–4 h, depending on the current water production). Then the water is directed to the oxygenation cascade. Just below the cascade is situated a dosage of chemical oxidant – potassium permanganate and coagulant PAX-18. The next step in water treatment is vertical coagulatory and sedimentation chambers with a contact time of 6–8 h. After the chambers to water which is directed to the horizontal settling tanks, calcium milk is dosed to raise the pH. The settling time in the settling tanks is several hours. The next step is the filtration of water on the filters at a rate of 1.5–3 m/h and the final disinfection with sodium hypochlorite, as shown in Fig. 1. The used conventional water treatment system allows to obtain water that meets all the requirements of the relevant regulations.

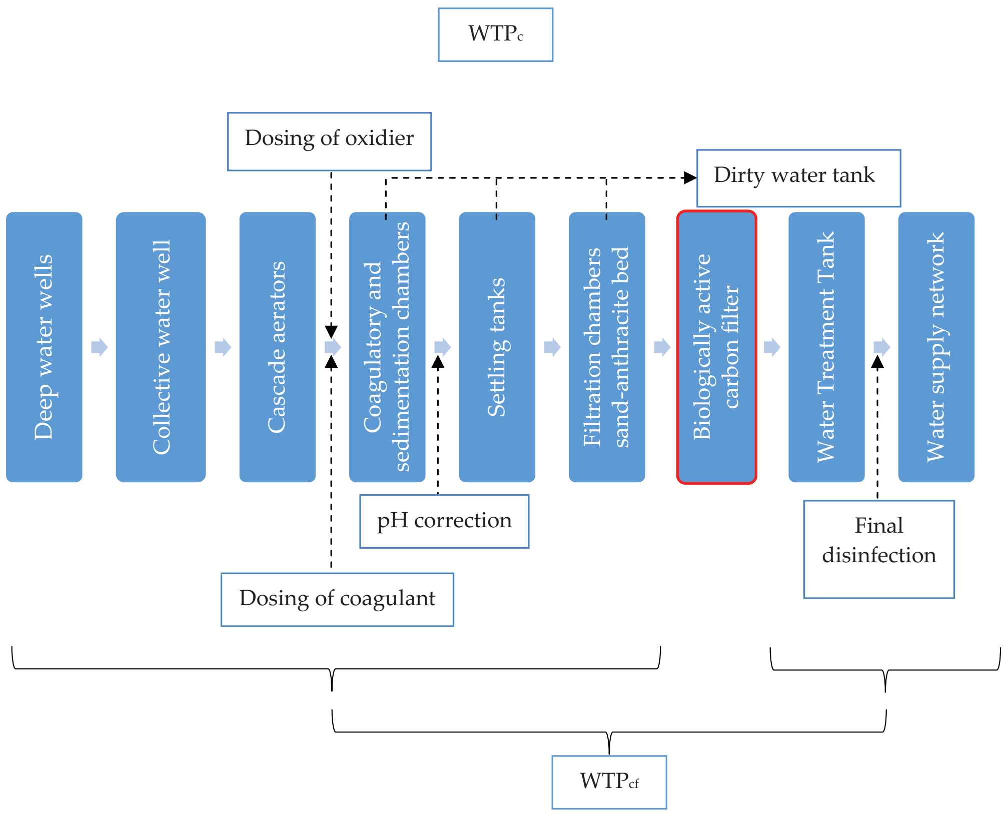

Fig. 1. Technological scheme of water purification, in red is marked the treatment with the use of carbon filter for WTP$_{cf}$ and conventional treatment process WTP$_c$.

2.2. Methodology of determination of physicochemical parameters of the treated water

Samples of water were collected twice a month from November 2015 to November 2016. The treated water was collected from the clean water tank prior to the final disinfection process, as in the scheme presented in Fig. 3.

The modified Kaplan and Newbold method [23] was used to determining the BDOC content using for this purpose colonized by autochthonous bacteria bioreactor with granular activated carbon.

2.3. Method of analysis and assessment of the risk of biological instability of water in the water supply network

The value of risk describes the so-called risk function $f(r)$, defined as the expected value of losses under specified operating conditions of the system which determine the vulnerability (resistance) of a system to a threat [24–26]. In the risk analysis, the priority is to identify potential threats. Risk assessment is a comparison of the obtained risk value with the assumed criteria value.

Mathematically, the risk of biological instability of water is defined as the expected value of exceeding the water quality parameters determining its biostability.

The following parameters determining the biostability of BDOC, $\sum N_{inorg}$ and PO_4^{3-}, based on the criteria contained in the work [27] and own assumptions were adopted.

The risk of loss of biostability of tap water is presented by the following relationship:

$$r = E(S_i \mid S_i \geq S_{tv}) = \Sigma_i P_i \times S_i, \qquad (1)$$

where $E(S_i \mid S_i \geq S_{tv})$ – expected value of exceedance of threshold values for water biostability and P_i – probability of exceedance of threshold values for water biostability.

And

$$S_{tv} = f(S_1, S_2, S_3), \qquad (2)$$

where S_1 is concentration of BDOC, gC m^{-3}; S_2 is concentration of N_{inorg}, gN m^{-3} and S_3 is concentration of PO_4^{3-}, gPO_4^{3-} m^{-3}.

For the analysis and risk assessment, the following threshold values of the parameters determining the biological stability of water were adopted: BDOC < 0.25 gC m^{-3}, $\sum N_{inorg} < 0.2$ gN m^{-3}, $PO_4^{3-} < 0.03$ gPO_4^{3-} m^{-3}.

The risk categorization is based on the value of the limit function $S_{tv} = f(S_1, S_2, S_3)$ according to the following relationships:

- tolerable risk (R_T) – water is biologically stable according to the presented criteria:

R_{T0}. $S_{tv} = f(S_1, S_2, S_3) \rightarrow (S_1 = \text{BDOC} < 0.25 \text{ gC·m}^{-3}) \wedge (S_2 = \sum N_{inorg} < 0.2 \text{ gN m}^{-3}) \wedge (S_3 = PO_4^{3-} < 0.03 \text{ g}PO_4^{3-} \text{ m}^{-3})$,

$\vee$

R_{TI}. $S_{tv} = f(S_1, S_2, S_3) \rightarrow (S_1 = \text{BDOC} < 0.25 \text{ gC m}^{-3}) \wedge (S_2 = \sum N_{inorg} < 0.2 \text{ gN m}^{-3}) \wedge (S_3 = PO_4^{3-} \geq 0.03 \text{ g } PO_4^{3-} \text{ m}^{-3})$,

$\vee$

R_{TII}. $S_{tv} = f(S_1, S_2, S_3) \rightarrow (S_1 = \text{BDOC} < 0.25 \text{ gC m}^{-3}) \wedge (S_2 = \sum N_{inorg} \geq 0.2 \text{ gN m}^{-3}) \wedge (S_3 = PO_4^{3-} < 0.03 \text{ g}PO_4^{3-} \text{ m}^{-3})$,

$\vee$

R_{TIII}. $S_{tv} = f(S_1, S_2, S_3) \rightarrow (S_1 = \text{BDOC} \geq 0.25 \text{ gC m}^{-3}) \wedge S_2 = \sum N_{inorg} < 0.2 \text{ gN m}^{-3}) \wedge (S_3 = PO_4^{3-} < 0.03 \text{ g}PO_4^{3-} \text{ m}^{-3})$.

The parameters determining the tolerable risk area indicate that the water supply parameters provide the required biological stability in the water supply network (acceptable level of safety [SL_T]).

- controlled risk – there are premises for maintaining the biological stability of water if the parameters shown in Table 1 are maintained:

R_{CI}. $S_{tv} = f(S_1, S_2, S_3) \rightarrow (S_1 = \text{BDOC} \geq 0.25 \text{ gC m}^{-3} \wedge S_2 = \sum N_{inorg} \geq 0.2 \text{ gN m}^{-3}) \wedge (S_3 = PO_4^{3-} < 0.03 \text{ g}PO_4^{3-} \text{ m}^{-3})$,

$\vee$

R_{CII}. $S_{tv} = f(S_1, S_2, S_3) \rightarrow (S_1 = \text{BDOC} \geq 0.25 \text{ gC m}^{-3}) \wedge (S_2 = \sum N_{inorg} < 0.2 \text{ gN m}^{-3}) \wedge (S_3 = PO_4^{3-} \geq 0.03 \text{ g}PO_4^{3-} \text{ m}^{-3})$,

$\vee$

R_{CIII}. $S_{tv} = f(S_1, S_2, S_3) \rightarrow (S_1 = \text{BDOC} < 0.25 \text{ gC m}^{-3}) \wedge (S_2 = \sum N_{inorg} \geq 0.2 \text{ gN m}^{-3}) \wedge (S_3 = PO_4^{3-} \geq 0.03 \text{ g}PO_4^{3-} \text{ m}^{-3})$.

The level of controlled risk means that the water quality parameters indicate the possibility of changes in the chemical stability of water in the water supply network (safety level which requires control and reduction [SL_C]).

- unacceptable risk (R_{una}) – water is biologically unstable at the following parameters:

$S_{tv} = f(S_1, S_2, S_3) \rightarrow (S_1 = \text{BDOC} \geq 0.25 \text{ gC m}^{-3}) \wedge (S_2 = \sum N_{inorg} \geq 0.2 \text{ gN m}^{-3}) \wedge (S_3 = PO_4^{3-} \geq 0.03 \text{ g}PO_4^{3-}\text{·m}^{-3})$.

The unacceptable risk means the occurrence of such water quality parameters that cause biological instability of water in the water supply network, which may result in the secondary contamination (and unacceptable safety level [SL_{UNA}]).

In Fig. 2 the criteria for the probability of exceeding BDOC, $\sum N_{inorg}$ and PO_4^{3-} parameters were presented, based on the work by Wolska [27].

Fig. 3 shows the determined expected values for exceeding the threshold values for water biostability for each risk category based on the limit value function $S_{tv} = f(S_1, S_2, S_3)$.

3. Results for the analysis and assessment of risk of lack of biological stability of tap water

The existing water treatment station very effectively removes iron and manganese. In the treated water, there are only traces of these impurities. On the other hand, the colour parameter is maintained at 10–15 Hazen, with an acceptable Hazen value of 15. In the discussed example, the colour was affected by organic substances – the content of TOC in the treated water was 7–12 mg C/dm^3, exceeding the value recommended by the WHO (5 mg C/dm^3).

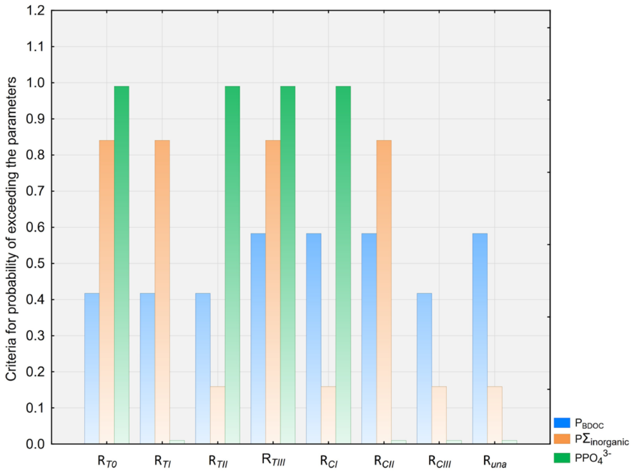

Fig. 2. Summary of the criteria for probability of exceeding the parameters BDOC, $\sum N_{\text{inorg}}$, PO_4^{3-}.

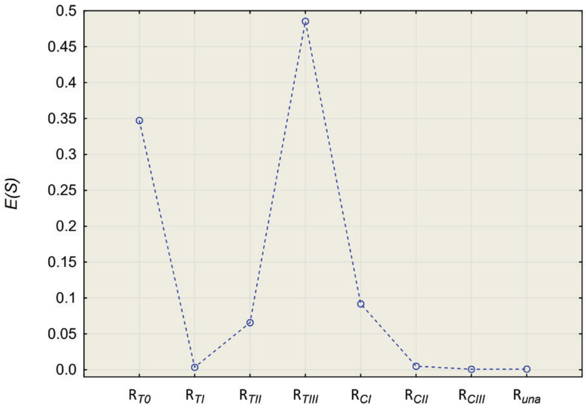

Fig. 3. Expected value of exceeding the threshold values for water biostability.

The analysis and risk assessment was carried out for two water treatment options:

- Underground water treated in conventional technology: coagulation, filtration and disinfection.
- Water treated in the technological system mentioned above, expanded by biofiltration on granular activated carbon.

The detailed analysis of BDOC, $\sum N_{\text{inorg}}$ and PO_4^{3-} parameters was carried out to analyse the risk of biological degradation.

Parameters of water treated in conventional manner (WTP_c) and with the use of carbon filter (WTP_{cf}) are shown in Fig. 4.

The treated water system was characterized by BDOC values ranging from 2.27 to 11.20 gC/m³. The range of variation in case of ΣN_{inorg}, was $0.16 \le \Sigma N_{\text{inorg}}$ (gN/m³) ≤ 1.20, while for phosphates PO_4^{3-} from 0,001 to 0,007 gPO_4^{3-}/m^3.

Taking into account the criteria mentioned in section 3.1, Fig. 5 shows the dependencies between individual safety criterion and the determined values of the individual parameters after the treatment process for two variants.

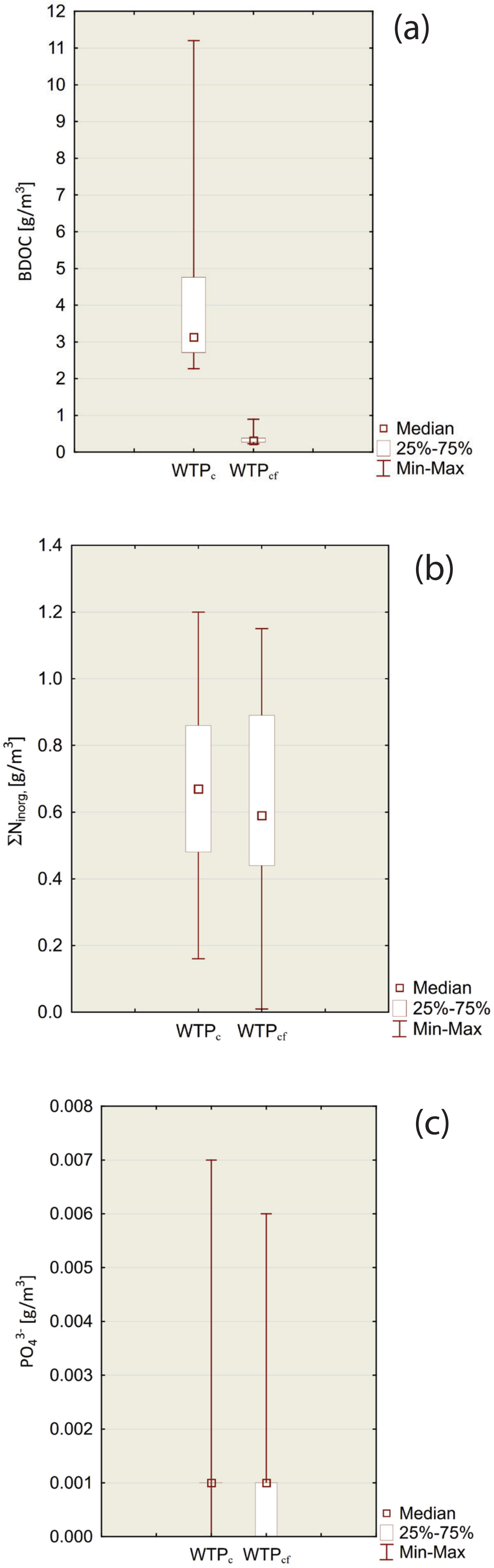

Fig. 4. Summary of parameters of water treated in the technological system increased by biofiltration on granular activated carbon (WTP_{cf}), and in a conventional way, for BDOC (a), $\sum N_{\text{inorg}}$ (b), and PO_4^{3-} (c).

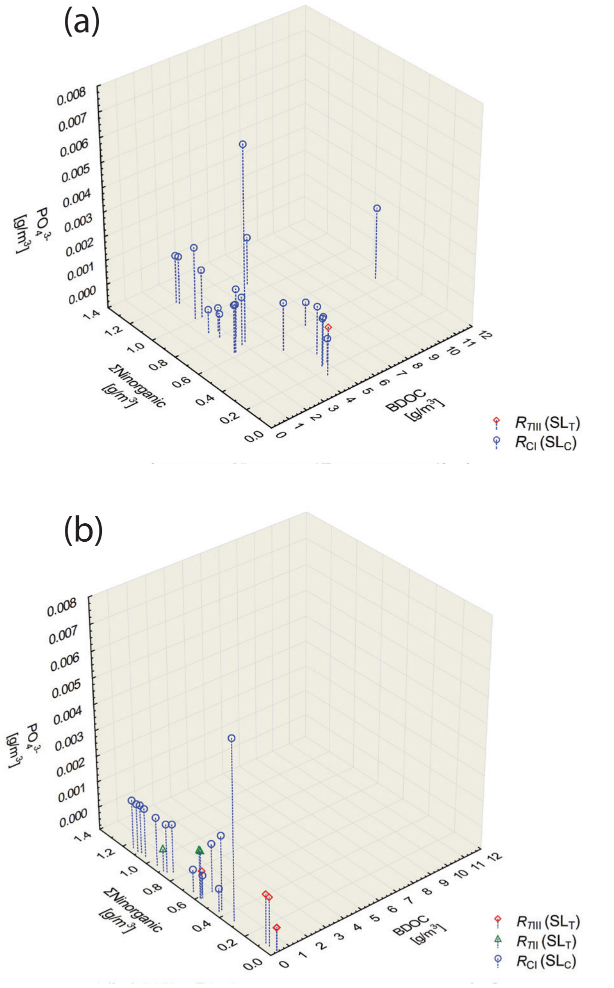

Fig. 5. Criteria for determining the individual safety levels taking into account parameters of water treated in a conventional system (a) and for water treated in a technological system increased by biofiltration on granulated activated carbon (b).

For the conventional water treatment, one sample is within tolerable risk $R_{TIII,}$ which corresponds to a tolerable safety level of SL_T, while the remaining 20 samples are in controlled risk R_{CI}. In the technological system increased by biofiltration on granular activated carbon 3 and 5 samples, are, respectively, the second (BDOC < 0.25 g/m³ and PO_4^{3-} < 0.03 g/m³) and the third category of tolerable risk ($\sum N_{inorg}$ < 0.2 g/m³ and PO_4^{3-} < 0.03 g/m³), so two of the three threshold concentrations are not exceeded, which proves more efficient process of water treatment. Other samples are included in the controlled risk category R_{CI}.

4. Discussion

The conventional water purification processes, that is, coagulation, sedimentation, filtration and disinfection, do not provide the effective elimination of biogenic substances and, in particular, BDOC and AOC. For this purpose, the process of filtration through granular activated carbon deposits is used more and more often. This process is characterized by the high efficiency of dissolved organic compounds removal, which additionally increases after the formation of biological membrane on the surface of the deposits, so apart from the adsorption process there is also biodegradation.

Water treatment in the technological system increased by biofiltration on granular activated carbon reduced the distinguished parameters of BDOC, ΣN_{inorg} and for PO_4^{3-}. The efficiency of water treatment extended by biofiltration on granular activated carbon is shown by the determined median and the arithmetic mean of the obtained results. Comparison of parameter changes, taking into consideration the parameters of water treated in the conventional system and water treated in the technological system increased by biofiltration on granular activated carbon, is as follows: the median and mean of BDOC are, respectively, 3.64 g/m³ and 0.06381 g/m³, for ΣN_{inorg}, respectively. 0.09 g/m³ and 0.06381 g/m³ and in case of PO_4^{3-} the median equals to zero and the mean is 0.00019 g/m³.

The sorptive properties of materials filling the biofilter and the ability to stop waterborne microorganisms cause that with the gradual depletion of the sorptive capacity of the biofilter filling the deposited biomass can take over its functions by sorbing the substances present in water and converting them into its building material and biochemical transformation products supplying cells with energy.

The biofilter filler has a large impact on the effectiveness of processes that take place in biosorption beds. Important is not only its granulation or actual surface but also its capability for producing stable connections between it and the microorganisms [28,29].

The effectiveness of BAFs in removal of various impurities is very high. The biological processes of water purification are becoming an alternative or a supplement for physicochemical methods. The oxidation of natural organic substances contained in the ozone-treated water, coupled with biological filtration, and their subsequent removal by adsorption on granulated active coals is a commonly used method for reduction of THM precursors [21].

There are two mechanisms that allow the removal of pollutants in the carbon bed: the adsorption of organic matter and, subsequently, the biochemical degradation of the adsorbed organic matter, as a result of microorganisms developing on the carbon bed. In the first stage of purification in the filter, adsorption is predominant. After a few weeks, with the appropriate oxygen and temperature conditions, microorganisms develop and the adsorption and biodegradation processes occur in parallel [30].

Biological changes are often slow, but because of the adsorption properties of carbon, organic molecules can stay on the carbon surface for long periods of time. With the gradual depletion of carbon sorption capacity, microbial biomass takes over its functions by sorbing substances present in water. Organic compounds cumulated in biomass are used for growth and respiration. It has been shown that the acceleration of biological growth in the water supply network can occur when the number of bacteria in the water entering the distribution is greater than 10^4 μt/mL [31,32]. In this example, the total number of bacteria in water after the biofiltration process did not exceed 5 cfu/mL [18]. BAF's well-chosen parameters demonstrate the small number of bacteria in water after biofiltration and the smooth transition from sorption to biodegradation.

In the case of waters containing natural organic matter and inorganic nitrogen, phosphate ions are essential [33,34]. Too low content of phosphate ions inhibits the growth of microorganisms to a much greater extent than for other biogens [3,35–39]. It was also claimed that the metabolic activity of microorganisms at 7°C was 50% lower than at 17°C. In the discussed case, the temperature of water entering the biofilter oscillated around 10°C, which could affect the activity and number of microorganisms. Hence, minimal changes in the content of nitrogen and phosphorus compounds in water after the biofiltration process are observed. The optimum ratio of biogenic C:N:P should be 100:10:1. Due to the lowest required phosphorus content, this element is the most limiting for growth of microorganisms and it can be assumed that the incomplete removal of biodegradable organic carbon was due to too low phosphorus content in water entering the biofilter. It is very difficult to fully remove nitrogen so lack of phosphorus and easily assimilated carbon is enough to reduce the growth of organisms to a level that guarantees lack of risk of secondary water pollution.

5. Conclusions

All the factors enabling the creation and development of biofilms in water distribution systems are so far not enough known. There is no doubt, however, that the main condition for the development of microorganisms is the presence of nutrients. Inorganic nitrogen and phosphorus compounds and the presence of BDOC are necessary for the development of all microorganisms. Due to the inability to remove inorganic nutrient substrates in conventional technology and the inadequate elimination of organic nutrients, it is necessary to add additional unit processes that will allow more efficient removal of biogenic substances. Such an opportunity creates a biofiltration process in which the filling of the biofilter plays a dual role: sorbent of pollutants and media for the growth of microorganisms. Due to the formation of biofilm, there is the removal of pollutants in the assimilation and biodegradation processes.

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