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Efficiency of removal of biogenic substances from water in the process of biofiltration

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ABSTRACT

The studies of changes in the level of biological stability of water throughout the process of biofiltration were conducted in real conditions for surface and infiltration water. In both cases, the most effective removal of organic substances was ascertained for the biodegradable fraction, whereby the majority of water samples after this process were characterized by the concentration of biodegradable dissolved organic carbon lower than the concentration limit in terms of the growth of micro-organisms. In the majority of water samples from both filtrates, successful removal of phosphate ions also ensured limiting the threat of micro-organism regrowth in distribution systems. Unfortunately, the concentration of inorganic nitrogen was not lower than the concentration limit in terms of biological stability in any of the filtrate samples. The most important factor affecting the efficiency of the removal of nutrient substrates from water was their content in the water prior to undergoing filtration.

Keywords: Biodegradation; Mineralization; Biological stability; Nutrient substrates; Biofilm

1. Introduction

The main cause of detrimental changes in water composition in distribution systems is considered to be water's instability [1,2], and above all its biological instability, which influences the possibility and intensity of micro-organism regrowth in distribution systems. As far as the potential threats to human beings are concerned, the most significant is the limitation of the development of heterotrophic micro-organisms, including pathogens. Thus, many authors [3–6] consider it sufficient to eliminate solely organic nutrient substrates in order to provide for water's biological stability. Organic substances which are assimilable by micro-organisms comprise only a small part of the natural organic material present in water [7]. These are usually substances with a low molecular mass, and therefore not susceptible to removal by conventional water treatment trials [8,9]. Reducing biodegradable dissolved organic carbon (BDOC) to very low levels which ensures the inhibition of heterotrophic micro-organisms is very difficult, and therefore it is necessary to eliminate the remaining nutrient substrates from the water. Jiang et al. [10] demonstrated that the factor which inhibits micro-organism regrowth in the water supply network can also be the low concentration of phosphate ions. Thus, ensuring

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the biological stability of water requires the removal of micro-organisms and their spores, as well as organic and inorganic nutrient substrates.

To achieve this goal, it is imperative to incorporate into conventional water treatment trial not only the processes which ensure the removal of organic substances of low molecular weight, but also the processes concerning removal of inorganic nitrogen compounds and phosphates. This condition is met primarily by biological processes which ensure the biodegradation of organic compounds as well as assimilation of nonorganic nutrient substrates [11–14]. In water treatment trials, this role is often played by filtration through a granular active carbon, on the surface of which [15–17] the biofilms's activity determines the efficiency of nutrient removal. Chaudhary et al. [18] demonstrated that depending on the conditions prevailing during the operation of the biofilters, biofilms of varied compositions develop upon their surface. This can help to explain the varied efficiency rates of elimination of individual fractions of organic substances from water which are obtained in studies led around the world.

The goal of the presented study was to determine the impact of the process of biofiltration in real conditions on changes in the content of organic and inorganic nutrient substrata.

2. Study methodology

The study of the impact of the process of biofiltration on the change in the content of biogenic substances was run in two water treatment plants, a surface water treatment plant and an infiltration water treatment plant. The water was subjected to pretreatment prior to undergoing biofiltration. Surface water was treated by volume coagulation, sedimentation, rapid sand filtration, and ozonation. Infiltration water, however, was treated by aeration, rapid sand filtration, and ozonation. The biofiltration process was conducted in both plants on rapid filters with a granular activated carbon (GAC) bed. The operating parameters of these beds are summarized in Table 1.

In both systems, the adsorption beds were covered with a biofilm, and their adsorptive capacity, due to the time of exploitation of the beds without regeneration, had been partially exhausted.

In both plants, the samples for the study purposes were collected from the inflow to the filter beds and the filtrate discharge pipelines. Water was collected regularly every two weeks, while maintaining the time of the flow of water through the beds. Transport of water to the laboratory occurred in thermostatic conditions, and at the site of water collection only, pH values and the concentration of ozone and dissolved oxygen were measured.

All samples were analyzed for the concentration of total organic carbon and dissolved organic carbon (TOC, DOC), BDOC as well as the content of inorganic nutrient substrates, i.e. PO_4^{3-}, $N_{inorg} = NH_4^+ + NH_3^-$).

Additionally, the samples were analyzed for the content of aggressive carbon dioxide (CO_{2aggr}), changes in the content of which one could indicate the biological activity of adsorption beds.

The concentration of non-biodegradable dissolved organic carbon (NBDOC) was determined from the differences between the concentrations of DOC and BDOC.

The limit values in terms of biological stability of water were determined based on the conclusions reached in literature [19–21], that is, 0.25 g C/m^3, 0.2 g N/m^3 and 0.03 g PO_4^{3-}/m^3 BDOC, N_{inorg} and PO_4^{3-}, respectively.

TOC and DOC content was measured with the aid of a TOC Analyzer produced by the company HACH-LANGE, and the concentration of BDOC was determined as the difference between the concentration of DOC in the sample prior to and post incubation in thermostatic conditions (22°C) micro-organisms according to Standard methods. The content of the inorganic nutrient substrates was determined by colorimetric methods using a spectrophotometer produced by the company Schimadzu. According to American Public Health Association, Standard methods for the examination of water and wastewater, 20th Edition, Washington, DC 1998

Table 1
Operating parameters of adsorption filters

Lp.	Parameter	Surface water	Infiltration water
1	Filter surface area, m^2	904.8	856.8
2	Speed of filtration, m/h	2.1–3.7	2.9–4.3
3	Empty bed contact time, min	27.1–45.6	27.6–41.3
4	Height of the bed, m	1.5	2.0

(phenate method- NH_4^+; calicylic acid methods- NO_3^- and ascorbic acid method- PO_4^{3-}).

3. Study results

Both waters subjected to biofiltration were characterized by a high variability of dissolved oxygen concentration (Table 2); however, the concentration in all the samples was sufficient to support the micro-organisms growth [22,23]. In the majority of surface water samples (91.7%), aggressive carbon dioxide was also present, which was caused by the lack of pH correction after the process of coagulation. On the other hand, in the infiltration water a concentration higher than 2 g CO_2/m^3 was determined in only two water samples.

All water samples of surface water contained greater amounts of organic substances than determined in the infiltration water. Both waters contained mainly dissolved organic substances, whose share was less than 50% of TOC in only one sample from each water plant, and in the remaining samples, its share ranged between 76.3–100.0 and 57.5–100.0%. Due to the use of the ozonation process prior to adsorption, the concentration of the biodegradable fraction of DOC in both waters was higher than that determined in untreated waters. In 75.0% of the surface water samples, the share of BDOC in DOC was lower than in infiltration water (Fig. 1). Despite the use of the ozonation process prior to biofiltration, the share of biodegradable organic material in TOC was smaller than that which had been determined in other studies [24], which can be related to the relatively low doses of ozone used in both treatment plants (average doses: 0.43 and 0.30 g $O_3/g\,C$ for surface and unfiltration waters).

Despite the increased content of the biodegradable fraction, its concentration was lower than the limit value in terms of biological stability in only one sample of surface water and two samples of infiltration water. Biofiltration contributed to an increase in the share of biologically stable samples (Table 3).

In most of the samples of infiltration water before biofiltration the concentration of phosphate ions was higher than in the surface water, and in 45.8% of samples, it was lower than the acceptable level for biological stability in water.

In contrast, the content of inorganic nitrogen compounds was high in both waters. Removal efficiency of nitrogen compounds was low and nitrate ions made up on average 94.8 and 88.9% of removed N_{inorg}.

As a consequence of biofiltration, lower pH values and lower concentration of dissolved oxygen were determined in all samples of both surface and infiltration water. This is due to the release into the water of acidic metabolic products of micro-organisms colonizing the GAC bed, and oxygen consumption by the micro-organisms and/or for oxidation of the admixtures present in the treated waters.

Additionally, an increase in the content of aggressive carbon dioxide was determined in all samples of the filtrates, which was directly proportional to the decrease in concentration of TOC (Fig. 2). This relationship was the same for both waters and demonstrates the course of mineralization of organic matter. Thus, it confirms the biological activity of the beds. Larger changes in the values of these water quality indicators were determined in relation to the more contaminated surface water.

Significantly more organic substances were removed from the surface water than from the infiltration water (Table 4), which, in accordance with

Table 2
Ranges of water quality indicators

Parameter	Unit	Surface water		Infiltration water	
		Before biofiltration	After biofiltration	Before biofiltration	After biofiltration
pH		6.76–7.75	6.70–7.62	7.01–7.82	6.92–7.60
O_2	$g\,O_2/m^3$	7.96–18.00	6.06–15.20	4.81–18.75	4.03/16.88
CO_{2agr}	$g\,CO_2/m^3$	0.00–7.36	2.00–11.44	0.00–2.74	0.00–5.94
TOC	$g\,C/m^3$	1.24–6.71	0.80–4.32	1.02–4.16	0.75–3.67
DOC	$g\,C/m^3$	1.15–5.70	0.75–3.82	0.82–3.70	0.41–3.42
BDOC	$g\,C/m^3$	0.23–0.77	0.10–0.35	0.23–0.51	0.04–0.31
NBDOC	$g\,C/m^3$	0.82–4.93	0.62–3.70	0.53–3.19	0.23–3.16
NH_4^+	$g\,N/m^3$	0.01–0.21	0.01–0.17	0.02–0.14	0.01–0.11
NH_3^-	$g\,N/m^3$	0.55–3.96	0.48–3.69	0.24–0.88	0.16–0.68
PO_4^{3-}	$g\,PO_4^{-3}/m^3$	0.00–0.05	0.00–0.03	0.01–0.09	0.01–0.06

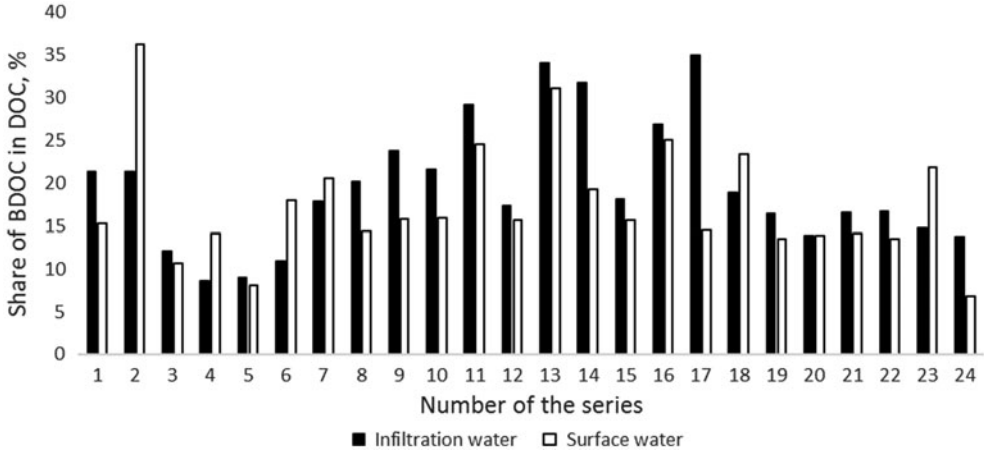

Fig. 1. Share of biodegradable fraction content in DOC.

Table 3
Share (%) biologically stable samples

	Surface water		Infiltration water	
	Before bio-filtration	After biofiltration	Before biofiltration	After biofiltration
BDOC	4.3	95.8	8.3	91.6
PO_4^{3-}	66.7	100.0	45.8	75.0
N_{inorg}	0.0	0.0	0.0	0.0

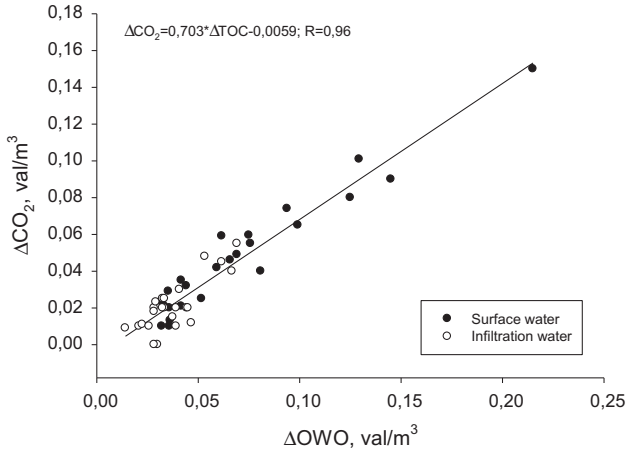

Fig. 2. The relationship between the decreased TOC content and the increase in the concentration of aggressive carbon dioxide.

literature reports [7,24], stems from the higher level of contamination of this water. The consequence of this is a decreased level of concentration of BDOC which is directly proportional to its content in the water subjected to biofiltration (Fig. 3).

Table 4
Range of decrease of the content of organic matter fractions (g C/m^3)

	TOC	DOC	BDOC	NBDOC
Surface	0.39–2.58	0.32–2.49	0.07–0.53	0.07–2.07
Infiltration	0.17–0.83	0.15–0.73	0.08–0.29	0.01–0.54

Despite the smallest amount of BDOC among the TOC removed, its share in the TOC removed was very large (Fig. 4). In most samples (66.7%), this share was higher in infiltration water, which resulted from the larger share of this fraction in TOC in water subjected to bio-filtration. A consequence of this was the higher average share of BDOC in removed TOC for infiltration water (57.9%) than in surface water (43.7%).

The large share of BDOC in removed TOC, given the low susceptibility to adsorption of this fraction, should be explained by its elimination chiefly by means of biodegradation [25]. In contrast, the small share of NBDOC in the removed TOC, given its large concentration and high susceptibility to adsorption, is the evidence of the partial exhaustion of the beds

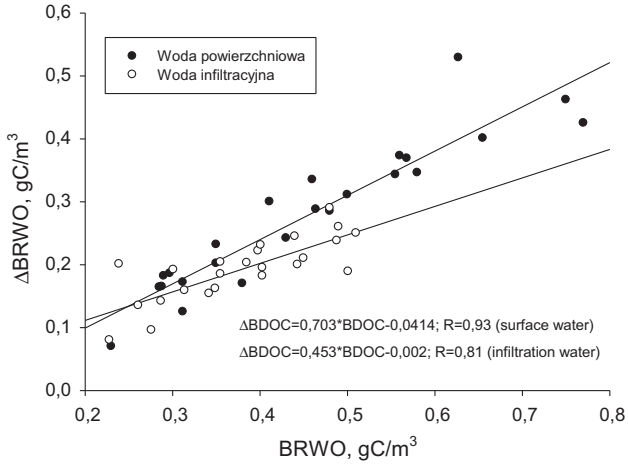

Fig. 3. Influence of the initial content of BDOC content on its reduction in the process of adsorption.

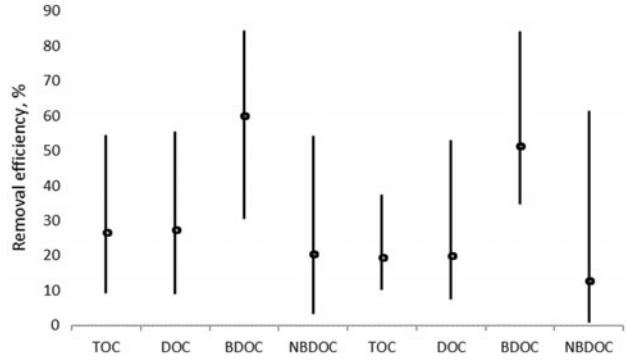

Fig. 5. Range and average efficiency of removal of organic substances fractions.

adsorptive capacities [26]. This hypothesis is confirmed by the studies of Fonseca et al. [23], which indicates a decrease in the effectiveness of the elimination of the fraction of organic matter in the process of biofiltration with the increasing exploitation time of the deposits. A consequence of this is the highest effectiveness of the removal of BDOC from both types of waters (Fig. 5) as well as a 83,3% increase in the share of biologically stable water samples due to the presence of this nutrient substrate (Table 3).

The achieved efficiencies of removal of BDOC (on average 59.8 and 51.1%) greatly surpassed the values which had been reached in other studies [27]. This should be explained by the use of significantly lower doses of ozone in the analyzed systems, which led to the formation of a much lower amount of BDOC in the process. Lee et al. [28] demonstrated that in biofiltration, around 50% of the BDOC formed in the process of ozonation is removed.

In contrast to Wang et al. [29], the present study has not determined any effect of the time of the flow through adsorption beds on the removal effectiveness of any of the analyzed organic substance fractions. The lack of such an effect in the analyzed water treatment systems should most likely be explained by the very slow flow of water through the beds (Table 1) due to a reduction of water consumption in recent years. This hypothesis is confirmed by the studies of Trang et al. [30], who demonstrated an increase in the effectiveness of elimination of TOC and BDOC in the process of biofiltration when the time of water flow through the bed was extended to 20 min. The effectiveness of removal of organic substances with an empty bed contact time of 25 min was already slightly smaller than the one determined for 20 min.

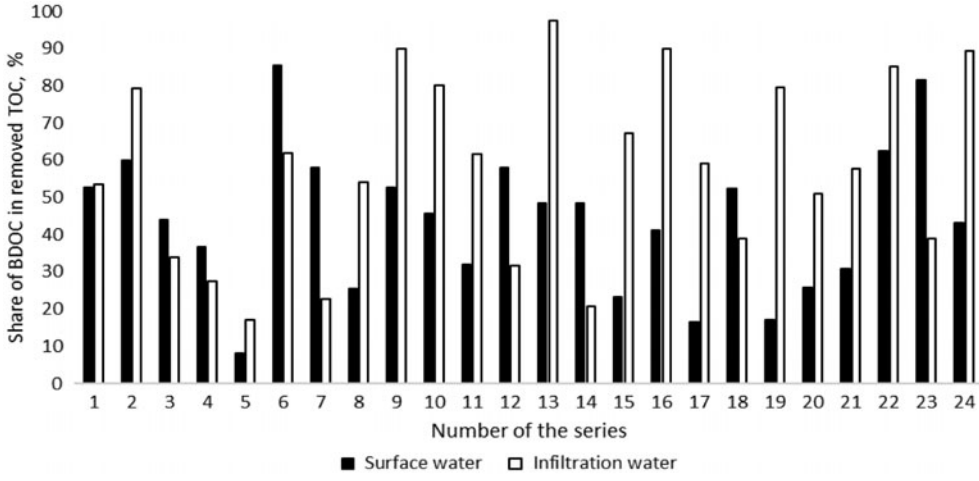

Fig. 4. Share of BDOC in removed TOC.

The reduction of inorganic nutrient substrates was mainly associated with their assimilation by micro-organisms inhabiting the adsorbent bed. The reduction of the concentration of inorganic nitrogen was within the range from 0.08–1.46 to 0.01–0.24 g N/m^3, respectively, for surface water and infiltration water, and its size was dependent on the content of N_{inorg} in the water undergoing biofiltration. Among the nitrogen compounds removed, nitrate ions dominated, constituting on average 89.8 and 71.7%. Ammonium ions were removed from the water through their assimilation by micro-organisms and/or their adsorption on the surfaces of solid particles present in the water. A decreased level of ammonia ions concentration is directly proportional to its content in the water subjected to biofiltration (Fig. 6).

Due to the low concentration of phosphate ions in the waters reaching the biologically active filters, the reduction in their content was also rather low being within the ranges, 0.00–0.03 g PO_4^{3-}/m^3, 0.00–0.06 g PO_4^{3-}/m^3. This reduction was, however, sufficient to ensure biological stability of 100 and 75% of water samples, due to the content of this nutrient substrate. The greater elimination of phosphate ions in infiltration water resulted from their greater presence in the water prior to undergoing biofiltration.

The water samples after biofiltration were characterized by a lower content of organic and inorganic nutrient substrates (Table 2) than the water before this process. The elimination of biogenic substances was large enough making the content of BDOC and phosphate ions in most water samples the factor limiting the micro-organisms regrowth in the treated water and, consequently, limiting the threat of secondary water contamination in the distribution system.

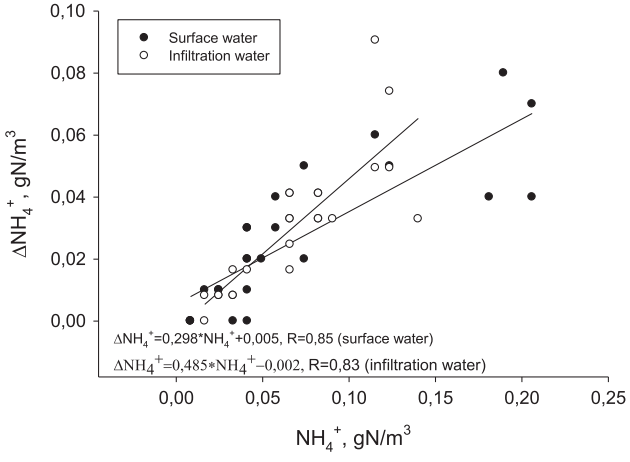

Fig. 6. The influence of the content of ammonium ions in water undergoing biofiltration on its reduction.

4. Conclusions

(1) The process of biofiltration in both analyzed cases guaranteed the reduction of all organic substance fractions. The efficiency of removal of TOC and its fraction mainly depends on the concentration of organic substances in water before biofiltration. Consequently, there was a much larger reduction in the concentration of TOC and its fractions from surface water.
(2) Successful removal of BDOC from surface and infiltration water resulted from its biodegradation by micro-organisms inhabiting the GAC bed, and not its adsorption. The low efficiency of removal of NBDOC, however, resulted from the partially exhausted adsorptive capacity of the beds.
(3) The reduction in the content of organic nutrient substrates was directly proportional to their content in the water inflow into the filter beds and ensured obtaining biological stability of most samples of treated water.
(4) The efficiency of removal of inorganic nitrogen compounds was insufficient to ensure biological stability of water
(5) The concentrations of BDOC and phosphate ions in the water after biofiltration are factors limiting the threat of micro-organisms regrowth in the water supply distribution network.
(6) A consequence of the over-dimensioning of the water treatment plants was the lack of an explicit influence of the speed of filtration, that is, the empty bed contact time, on the efficiency of the elimination of nutrient substrates.

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