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Risk assessment and the effect of chlorination on the content of forms of biodegradable organic carbon in water intended for consumption

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ABSTRACT

The study examined the content of biodegradable dissolved organic carbon (BDOC) and assimilable organic carbon (AOC) in water intended for consumption. For the research, groundwater samples collected from four water treatment plants of a water supply company located in the Silesian Voivodeship (Poland) were used. The research results can be used for planning and making decisions regarding the health risk of water intended for consumption. Evaluation of the content of BDOC and AOC as determinants of water biological stability may constitute a new concept for assessing the risk of microbiological hazards according to the implementation of water safety plans.

Keywords: Assimilable organic carbon; Biodegradable organic carbon; Chlorination; Water

1. Introduction

Proper chemical and biological quality of water is the most important criterion of its suitability for use. Therefore, in order for water to be suitable for consumption, it must meet the numbers of requirements specified in relevant legal acts. In Poland, regulations regarding the quantitative and qualitative composition of water intended for consumption are included in the Regulation of the Minister of Health on the quality of water intended for human consumption [1]. Guidelines regarding the acceptable values of water quality parameters are also provided by other organizations such as the World Health Organization (WHO) or regional organizations, that is, the United States Environmental Protection Agency. The Council of the European Union also issued Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption. Permissible values of water quality parameters vary in many countries, which is most often caused by the degree of pollution of natural waters in individual countries as well as technical and economic possibilities of water treatment. Analysis of the required quantitative and qualitative composition of water intended for economic usage and consumption clearly indicates that the number and concentration of undesirable substances in water is systematically growing [2,3].

The content of various types of microorganisms and substances in water, which can be the source of carbon and energy necessary for the development and growth of microorganisms, is the main problem of water treatment plants (WTP). Most of the oxidation reactions used in WTP lead to the formation of oxidized by-products such as organic acids, aldehydes, and other unidentified compounds [4,5]. The substances that have the greatest impact on the development and growth of microorganisms in the water are organic substances, in particular their biodegradable part, that is, biodegradable dissolved organic carbon (BDOC) [6–9]. Huck [10] provides a definition in which BDOC is a part of organic carbon that can be mineralized by heterotrophic microorganisms in water. This phenomenon is related

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to secondary microbial contamination in purified water, usually in drinking water distribution systems [10,11]. Unfortunately, it is not a standard practice in Poland nor in the world to determine the content of biodegradable organic matter. BDOC is not a parameter regulated by law, and the formation of biodegradable organic carbon is often overlooked by operators of WTP. Moreover, there is no general understanding that the disintegration of disinfectants is directly related to an increase in BDOC.

From previous studies, it appears that the average BDOC content in natural waters ranges from 0.1 to 0.5 mg L^{-1}. The fraction that can be considered a direct indicator associated with secondary microbial contamination during water distribution is the so-called assimilable organic carbon (AOC) [12–14]. AOC is a part of BDOC and correlates with the occurrence of coliform bacteria and an increased amount of heterotrophic bacteria (HPC) [15]. Although the content of AOC and BDOC in water intended for human consumption is not regulated by any legal act, their limit content has been determined, at which there is a risk of secondary water pollution in the water supply network. An arbitrary limit of AOC content in purified water was accepted, which is <1–2 g C m^{-3}. In the Netherlands, the accepted limit value for AOC is 0.01 mg L^{-1} [16], in Switzerland equal to 0.032 mg L^{-1} [17]. In the US, two AOC limit values have been established to prevent biofilm formation of 0.058 and 0.046 mg L^{-1} for summer and winter season, respectively [18]. In the case of BDOC, in European distribution systems, where the residual chlorine concentration is generally lower than 0.2 mg of free chlorine per liter, BDOC limit values have been established in the range of 0.13–0.20 mg L^{-1}. However, other researchers believe that the qualitative and quantitative composition of substances contained in water depends to a large extent on a given water supply system, therefore it is difficult to establish general guidelines regarding BDOC and AOC threshold values [6].

In Poland, the new Regulation on the quality of water intended for human consumption [1] introduces the term "risk assessment," defined as the process of hazard identification and risk analysis. As part of the risk assessment, a range of water parameters to be monitored can be extended if it is not sufficient to ensure that water supplied to the consumers meets the requirements stipulated in the Regulation. The introduction of the human health risk assessment in the new Regulation corresponds to the global trends, concerning the analysis of various components of risk in order to execute not only financial goals, but also social, cultural, and environmental [19], including the implementation of water safety plans (WSPs) [20]. The WHO and the International Water Association promote a preventive approach to risk management to ensure safe drinking water. WSPs cover all stages of water supply and aim to prevent and minimize contamination of source waters and prevent contamination during storage, distribution, and handling of drinking water [21]. Validation of BDOC and AOC content as determinants of water biological stability represents a new concept for assessing the risk of microbiological hazards according to the new Regulation.

During the process of water treatment and distribution, it is therefore important to evaluate the content of BDOC and AOC, because as biodegradable by-products these substances can be formed at every stage of water purification. This forces WTP to adjust the treatment parameters in a way to eliminate, with maximum efficiency, the formation of by-products in a biodegradable form [11]. Therefore, content assessment, forecasting, and monitoring of BDOC and AOC concentrations in water after the disinfection process have a very important sense, leading to minimizing their negative impact on the quality composition of water intended for consumption and the overall condition of the water supply network [22].

Therefore, the aim of the research was to determine the content of selected organic carbon forms, that is, total organic carbon (TOC), dissolved organic carbon (DOC), BDOC, and AOC in water intended for consumption.

2. Materials and research methodology

2.1. Characteristics of water sources

For the research, groundwater samples collected from four WTP of a water supply company located in the Silesian Voivodeship (Poland) were used. The company treats water from intakes designated in the article with symbols: *M*, *W*, *L*, and *R* (Table 1).

For testing, samples of raw water were taken from individual intakes and of treated water after disinfection and from consumer taps. Raw water *M* was collected from the right and left water reservoirs. In the case of *W* intake, raw water was collected from wells and from the source (Table 1). For each intake, raw water for testing was sampled from selected wells, operating during the research period. Water from the *M* intake originated from wells of depths from 37 to 133 m, water from the *W* intake originated from wells of depths from 42 to 71 m and from a source of 3 m depth, water from the *L* intake originated from wells of depths from 69 to 90 m, water from the *R* intake originated from a well of 460 m depth. Currently, the central waterworks meets its basic tasks, operating 60 deep wells and one source, grouped in five basics, and 15 auxiliary intakes.

Table 1
List of sampling points in study object

Sampling point	*M*	*W*	*L*	*R*
The natural	The right reservoir	The well	The well	The well
raw waters	The left reservoir	The source		
The treated	The pump station	The pump station	The pump station	The pump station (right and left)
water	A consumer tap	A consumer tap	A consumer tap	A consumer tap

The main water supply network consists primarily of pipes with a diameter greater than 250 mm made of cast iron, while the distribution water supply network is made of:

- gray cast iron – 39%,
- polyvinyl chloride (PVC) – 35.5%,
- steel – 6%,
- asbestos-cement – 3%,
- polyethylene – 15.5%,
- ductile iron – 1%.

Water supply connections are made of steel and polyethylene pipes.

The total production capacity of the groundwater intakes of the company equals to 6,105 $m^3 h^{-1}$ and 145,284 $m^3 d^{-1}$.

Water samples were collected from points of the intakes, at selected, individual stages of the water purification process, from the pump stations and from residential buildings – from consumers tap. Samples were collected five times, once every 30 d, from November to March. Three liters of water were collected for testing from individual intake points and the TOC, DOC, BDOC, and AOC parameters were determined.

2.2. Research methodology

2.2.1. TOC analysis

TOC assays were conducted with the analyzer "TOC analyzer Multi N/C 2100." For the research, 100 mL samples of analyzed waters were prepared. The inorganic carbon fraction was stripped by stirring. The limit of quantification of the method was 0.01 mg C L^{-1}.

2.2.2. DOC analysis

In order to obtain a soluble fraction of organic carbon, water samples were filtered through a 25 mm diameter membrane with a mesh diameter of 0.45 μm made of PTFE. The DOC assays were conducted with the analyzer "TOC analyzer Multi N/C 2100." For the research, 100 mL samples of analyzed waters were prepared. The inorganic carbon fraction was stripped by stirring. Standard deviation ranged from 0.01 to 0.03 mg L^{-1} for the analyzed waters.

2.2.3. BDOC analysis

Analysis of BDOC content was carried out using the Joret method. Several modifications were used so that the given test procedure was as optimal as possible for the analysis of individual types of water samples.

BDOC content was determined as the difference between the DOC content before the inoculation (DOC_0) and after 5 or 7 d of incubation after the inoculation (DOC_n) where $n = 5$ or 7 according to Eq. (1).

$$BDOC = DOC_0 - DOC_n \quad (1)$$

Method 2 takes into account conducted modifications. Standard deviation ranged from 0.001 to 0.004 mg L^{-1} for the analyzed waters.

For samples with the inoculum of the flora characteristic of a given water sample, reproducible results were obtained with a 5 d incubation. Samples without inoculum required a 7 d incubation.

2.2.4. Assimilable organic carbon

AOC analysis was conducted on the basis of Standard Methods [23]. AOC determination was carried out twice for each sample. Standard deviation ranged from 0.001 to 0.004 mg L^{-1} for the analyzed waters.

For AOC determination, *Pseudomonas fluorescens P-17* strain (ATCC 49642) and *NOX* strain from the *Spirillum* family (ATCC 49643) were used [24–26]. The research consisted in measuring the growth to the maximum density of a small inoculum in a batch culture of pasteurized analyzed water. *P. fluorescens P-17* and *Spirillum NOX* were determined by the HPC method in order to calculate the number of heterotrophic organisms, and the viable cell density is converted to AOC concentrations by the empirically obtained efficiency coefficient for growth of *P. fluorescens P-17* on acetate carbon, and for *Spirillum NOX* on oxalate carbon.

In order to prepare the inoculum, the suspension was made by rinsing 24 h cultures carried out on R2A agar slants into 2–3 mL filtered (through a 0.2 μm filter) autoclaved water sample. Pre-propagated cultures were stored at 6°C. They constituted the material for the inoculation of water samples. Optical density of the prepared suspension, measured using an Eppendorf photometer, was equal to 0.132 (0.5 standard according to McFarland scale), which corresponds to a bacterial cell concentration of 1.5×10^8 CFU mL^{-1}.

The next stage was the preparation of analyzed water samples. Collected water samples were transferred directly to vials. Part of the vials were designed for AOC measurements and for the control of microorganism growth. Chlorinated water was neutralized with sodium thiosulphate. Then, the vials were pasteurized in a water bath.

In order to inoculate the analyzed water sample, 1 mL of the previously prepared suspension from the last dilution was taken and transferred to a flask with a sample of water-cooled down after pasteurization. The vials were stored in the dark for 2 weeks. On day 7, 8, and 9 of incubation, the vials were withdrawn from the incubator, and analysis was conducted in duplicate.

The bacterial growth was controlled daily using the surface spread technique (plate method, HPC). Bacterial cultures were performed in triplicate, simultaneously with conducting culture of control samples.

Colonies of *P. fluorescens P-17* first appeared on the plates. They had a diameter of 3–4 mm and were characterized by a yellow color. The *NOX* colonies were small (diameter of 1–2 mm) white spots.

After n days (depending on the series), the maximum number of colonies was obtained, which was calculated into AOC concentration in the analyzed water sample according to Eq. (2) in Standards Methods [23].

2.2.4.1. Determination of yield of P-17 and NOX

The yields of *P-17* and *NOX* on model carbon compounds should be constant if organic carbon is limiting and

the incubation temperature is kept constant. It is acceptable to use the previously derived empirical yield values of 4.1×10^6 CFU P-17/μg acetate-C, 1.2×10^7 CFU-NOX/μg acetate-C, and 2.9×10^6 CFU-NOX/μg oxalate-C at 15°C. When the empirical yield factors 5 are used, the equation becomes:

$$\mu g\ AOC\ L^{-1} = [(\text{mean P-17 CFU } mL^{-1}) (\mu g \text{ acetate-C}/4.1 \times 10^6 CFU) + (\text{mean NOX CFU } mL^{-1}) (\mu g \text{ oxalate-C}/2.9 \times 10^6 CFU)]\ (1{,}000\ mL\ L^{-1}) \quad (2)$$

Comparing the separate incubation of the strains with the co-inoculation samples of *P. fluorescens P17* and *Spirillum NOX*, it was observed that the joint growth was up to 3% of the colony-forming units lower than in the case of separate incubation. In the further part of the research, data from separate incubation were used.

The content of BDOC and AOC in samples stored for 7 d at a temperature of approximately 4°C was also compared. The examined parameters in stored identical samples were higher on average by 30%–60% than those tested on the day of sample collection. Therefore, the assays were carried out on the day of sample collection.

The statistics of the significance of changes in the content of the analyzed forms of organic carbon in raw water and after the disinfection and distribution process were evaluated by the t-student t_d test according to the Standards method recommendation. This test was used in order to compare (verify if there exist statistically significant differences) average contents of indicators in raw water and after the process. The characteristic value of *t*-student distribution was adopted depending on the parallelly conducted determination of the above indicators. The number specifying the degree of freedom for the results carried out in triplicate was 4. Values lower than the critical value $t_{0.05} = 2.776$ indicated that the change in the average content of BDOC and AOC in raw water and after disinfection and distribution processes is not statistically significant. Other average values differed from each other statistically significantly. For BDOC, the obtained test statistic values of *t*-student ranged from 1.86 (sample *R* the pump station) to 10.10 (sample *W* the pump station). For AOC, obtained test statistic values of *t*-student ranged from 4.07 (sample *R* a consumer tap) to 12.90 (sample *W* the pump station).

3. Results and discussion

3.1. TOC, DOC, BDOC, and AOC content

The TOC content in water from the *M*, *W*, *L*, and *R* intakes is presented in Figs. 1 and 2. In Table 2, the content of DOC, BDOC, and AOC in analyzed water samples is presented. Presented results are the average values of five samplings from the period of research.

Raw water *W* was characterized by a TOC content equal to 1.01 mg L^{-1}. In raw water *M* from both reservoirs (right and left) the TOC content was equal to 0.73 mg L^{-1}. In pump stations, the TOC content was determined at 0.94 and 0.91 mg L^{-1} for *W* and *M* water, respectively. It was observed that the TOC content in water from the *M* intake increased after the disinfection process by 21% (raw water – water from the pump station) (Fig. 1). Analyzing the TOC variability for individual collecting points, the highest deviation value of 0.2 mg L^{-1} was observed for samples *W* raw water and water is taken from the pump station and a consumer tap (Fig. 2). For samples from the *L* and *R* intakes at individual water intake points, the standard deviation value ranged from 0.05 to 0.1 mg L^{-1}. This increase may be caused by precipitation or release of organic compounds from water supply devices and pipelines or deposits of various substances that have previously been clogged on the walls of pipelines. The reduction in the amount of TOC during the treatment processes is confirmed by literature data [27].

The TOC content in raw water from the *L* intake was equal to 1.78 mg L^{-1} and from the *R* intake 1.16 mg L^{-1}. In the case of water collected from the pump station, the TOC content was 1.17 and 1.41 mg L^{-1}, respectively, while in water

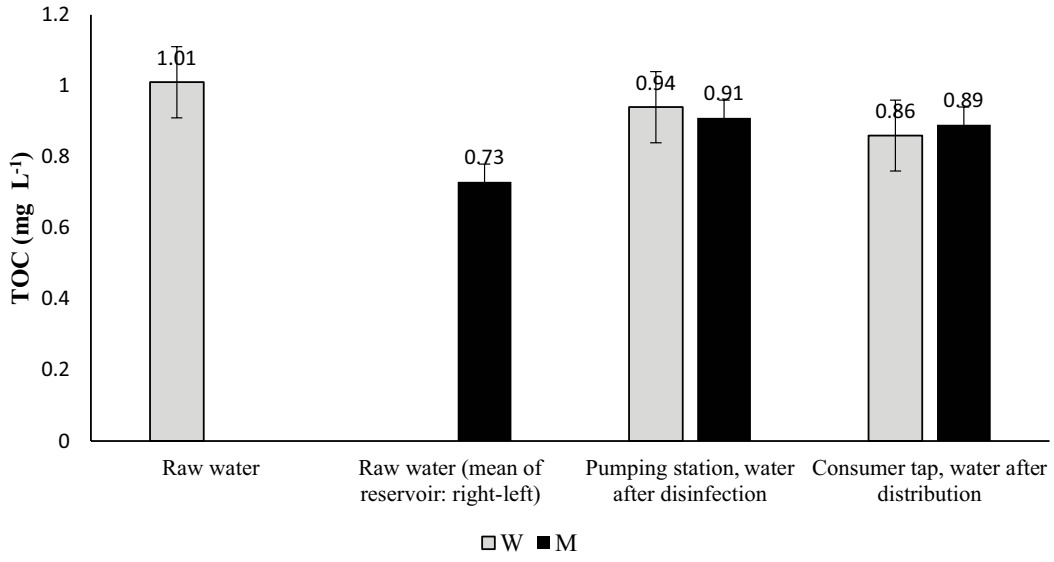

Fig. 1. Content of TOC in water from the *W* and *M* intakes.

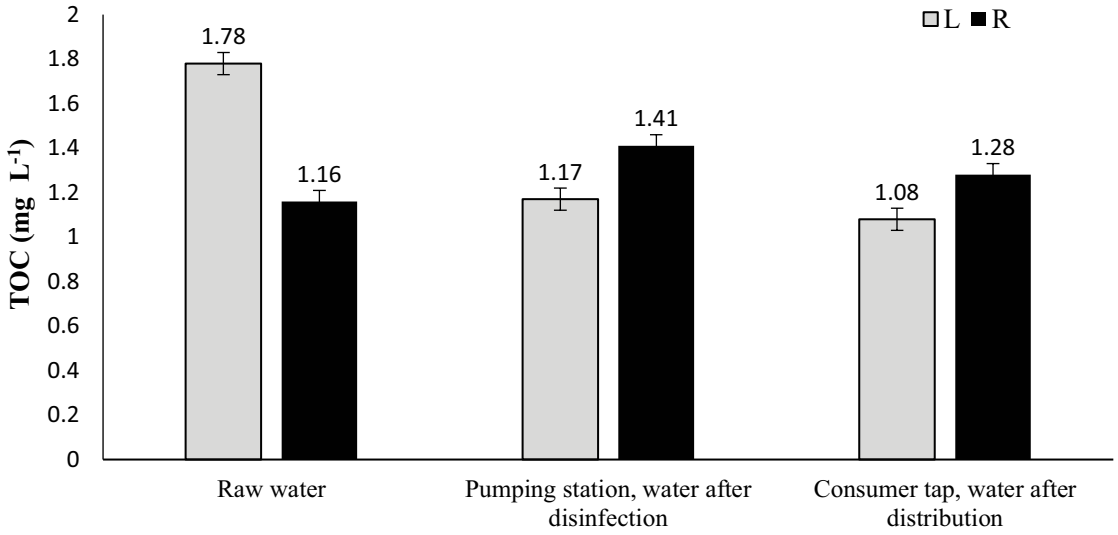

Fig. 2. Content of TOC in water from the *L* and *R* intakes.

from a consumer tap the TOC content was 1.08 to 1.28 mg L^{-1}, for the *L* and *R* intake, respectively. It was observed that the TOC content in water from the *L* intake decreased after the disinfection process (raw water – water from the pump station) by 39%.

According to Świderska-Bróż [28], a reduction of TOC content in the water distribution system can be caused by both precipitation and sedimentation of organic chemical substances in the pores of the inner walls of the water supply pipes. Other literature data show that the reason for the decrease in the TOC content is the usage of these substances as a source of carbon and energy for the development and growth of microorganisms in water [29,30]. According to the literature, changes of TOC in water during its distribution may be a result of such processes as the release of organic components of sediments into the water, consumption of organic substances by microorganisms, and chemical mineralization of these substances [31].

The DOC content in water samples from the *W* intake was at a similar level of 0.5 mg L^{-1} (the well), 0.85 mg L^{-1} (the source), 0.56 mg L^{-1} for the pump station, and a consumer tap (Table 2). In water from the *M* intake, the DOC content for right and left reservoir amounted to 0.46 and 0.48 mg L^{-1}, in water from the pump station 0.65 mg L^{-1}, and in water from a consumer tap 0.61 mg L^{-1}. In water from the *L* intake, the DOC content from the well, the pump station, and a consumer tap was equal to 1.2, 0.72, and 0.65 mg L^{-1}, respectively. In water from the *R* intake, the DOC content was from 0.74 (the well) to 1.00 mg L^{-1} (the left pump station). Analyzing the DOC variability for individual collection points, the highest standard deviation (0.003 mg L^{-1}) was demonstrated for samples *M* and *L* taken from the right, the left reservoir, the well, and the pump station, respectively. For all *R* samples, the standard deviation was at the same level of 0.002 mg L^{-1}. In order to verify the determination of BDOC content in the analyzed waters, a test method with inoculation (Joret method) and without inoculation was used (Table 2). The experiment demonstrated that the results obtained with both methods are similar. Not using the inoculation significantly simplifies the method (it does not require a microbiological laboratory) but it extends it. Therefore, the results of BDOC obtained using the Joret method are given in the further part of the research.

Changes in the BDOC content were analyzed in relation to raw waters for the *W*, *M*, *L*, and *R* intakes, respectively. Analyzing BDOC variability for individual collection points, the highest standard deviation value of 0.004 mg L^{-1} was observed for samples taken from the well (the *W*, *L* intakes) and from the right and left reservoir (the *M* intake). For water samples taken from a consumer tap, for all intakes, the standard deviation value was lower and it amounted to 0.002 mg L^{-1}. For the *W* intake, it was shown that the BDOC content in water from the well was equal to 0.08 mg L^{-1} and from the source 0.02 mg L^{-1}. The BDOC content in the water after disinfection, collected from the pump station, amounted to 0.052 mg L^{-1}. In water collected from a consumer tap, the BDOC content was at the level of 0.039 mg L^{-1}. In the case of water from the *W* intake, the largest increase in BDOC content was observed both after disinfection (by 160%) as well as in water collected at a consumer tap by 95% (Fig. 3). For the *M* intake, it was shown than the BDOC content in the right and left reservoir was 0.035 mg L^{-1}. The content of BDOC in water after disinfection collected from the pump station was equal to 0.059 mg L^{-1}. In water collected from a consumer tap, the BDOC content was at the level of 0.045 mg L^{-1}. An upward trend in the BDOC content was also observed for this intake. After the disinfection and distribution of water, the BDOC content increased by 69% and 29%, respectively (Fig. 3). For the *L* intake, the BDOC content in the well water was shown to be equal to 0.095 mg L^{-1}. The content of BDOC in disinfected water collected from the pump station amounted to 0.040 mg L^{-1}. In water collected from a consumer tap, the BDOC content was at the level of 0.072 mg L^{-1}. It was shown that in water from the *L* intake the BDOC content after disinfection decreased by 58%, and in the water taken from a consumer tap by 24%. For the *R* intake, it was shown that the BDOC content in water from the well was equal

Table 2
DOC, BDOC, and AOC content (mg L^{-1}) in the waters

Points of the intakes		DOC				BDOC (Joret method – with inoculation)				BDOC (without inoculation)				AOC			
		Mean	Minimum	Maximum	SD	Mean	Minimum	Maximum	SD	Mean	Minimum	Maximum	SD	Mean	Minimum	Maximum	SD
W	The well	0.50	0.48	0.53	0.02	0.080	0.078	0.085	0.004	0.065	0.062	0.068	0.003	0.017	0.013	0.019	0.003
	The source	0.85	0.83	0.87	0.01	0.020	0.017	0.022	0.003	0.010	0.010	0.017	0.005	0.005	0.003	0.007	0.002
	The pump station	0.56	0.53	0.59	0.02	0.052	0.049	0.054	0.003	0.044	0.040	0.046	0.002	0.014	0.013	0.017	0.001
	A consumer tap	0.56	0.54	0.58	0.02	0.039	0.037	0.041	0.002	0.034	0.033	0.035	0.001	0.009	0.007	0.014	0.003
M	The right reservoir	0.46	0.43	0.49	0.03	0.035	0.031	0.040	0.004	0.033	0.030	0.035	0.002	0.015	0.011	0.018	0.003
	The left reservoir	0.48	0.44	0.53	0.03	0.035	0.033	0.038	0.002	0.028	0.026	0.030	0.002	0.015	0.011	0.020	0.003
	The pump station	0.65	0.62	0.67	0.02	0.059	0.057	0.062	0.002	0.043	0.041	0.047	0.002	0.011	0.005	0.015	0.004
	A consumer	0.61	0.60	0.63	0.01	0.045	0.041	0.049	0.002	0.037	0.034	0.039	0.002	0.008	0.006	0.011	0.002
L	The well	1.20	1.11	1.30	0.03	0.095	0.092	0.099	0.004	0.089	0.085	0.093	0.003	0.012	0.011	0.012	0.001
	The pump station	0.72	0.68	0.75	0.03	0.040	0.037	0.042	0.002	0.038	0.036	0.040	0.002	0.009	0.007	0.014	0.004
	A consumer tap	0.65	0.64	0.65	0.01	0.072	0.070	0.075	0.002	0.068	0.065	0.072	0.003	0.005	0.005	0.010	0.002
R	The well	0.74	0.71	0.76	0.02	0.065	0.061	0.067	0.003	0.070	0.068	0.072	0.002	0.009	0.007	0.012	0.002
	The right pump station	1.00	0.98	1.03	0.02	0.063	0.059	0.066	0.003	0.062	0.060	0.065	0.002	0.011	0.006	0.016	0.004
	The left pump station	0.98	0.96	1.00	0.02	0.065	0.063	0.067	0.002	0.055	0.053	0.057	0.002	0.011	0.006	0.016	0.004
	A consumer tap	0.89	0.86	0.90	0.02	0.055	0.052	0.058	0.002	0.040	0.037	0.044	0.003	0.008	0.006	0.012	0.002

SD: standard deviation

to 0.065 mg L^{-1}. The BDOC content in the water after disinfection, collected from the pump station, was 0.063 and 0.065 mg L^{-1}. In water collected from a consumer tap, the BDOC content was at the level of 0.055 mg L^{-1}. In water from the *R* intake, after the disinfection process, no change in BDOC content was found, whereas after distribution, the BDOC content decreased by 15% (Fig. 3).

Analyzing the BDOC variability for individual collection points, the highest standard deviation value of 0.004 mg L^{-1} was observed for samples taken from the well (the *W*, *L* intakes) and from the right and left reservoir (the *M* intake). For water samples collected at a consumer tap, for all intakes, the standard deviation value was lower and amounted to 0.002 mg L^{-1}. Analyzing the changes in AOC in water from the *W* intake, it was demonstrated that AOC content in water from the well amounted to 0.017 mg L^{-1} and from the source amounted to 0.005 mg L^{-1}. AOC content in water after disinfection, collected from the pump station amounted to 0.014 mg L^{-1}. In water collected from a consumer tap, AOC content was at 0.009 mg L^{-1}. Thus, AOC content in water from the *W* intake increased by 180% after the disinfection process and by 80% after the distribution process (Fig. 4). In water from the *M* intake from the right and left reservoir it amounted to 0.015 mg L^{-1}. AOC content in water after disinfection, collected from the pump station amounted to 0.011 mg L^{-1}. In water taken from a consumer tap, AOC content was at 0.008 mg L^{-1}. In the case of water from the *M* intake, it was observed that AOC content after disinfection and distribution process decreased, respectively, by 27% and 47%.

When analyzing AOC changes in water from the *L* intake, it was shown that AOC content in well water amounted to 0.012 mg L^{-1}. AOC content in water after disinfection, collected from the pump station, was equal to 0.009 mg L^{-1}. In water taken from a consumer tap, AOC content was at 0.005 mg L^{-1}. AOC content in water from the *L* intake decreased by 25.0% after the disinfection process and decreased by 58% after the distribution process (Fig. 4).

In the case of water from the *R* intake, AOC content in the well water amounted to 0.009 mg L^{-1}. AOC content in water after disinfection, collected from the pump station, both right and left, was the same and amounted to 0.011 mg L^{-1}. In water collected from a consumer tap, AOC content was at 0.008 mg L^{-1}. Therefore, after disinfection, the content of AOC increased by 22%, and after the distribution process decreased by 11%. The reduction of AOC by water treatment was shown to be a function of the raw water quality and the particular treatment process which is confirmed by the study by Charnock and Kjønnø [32]. Treatment plants are using limited or no specific measures for removal of DOC and post-chlorination, increase AOC levels. According to the literature data, a specific reclaimed water source (secondary effluent) showed a lower specific AOC level (normalized AOC per unit of DOC) than the drinking water source. The low specific AOC level in reclaimed water source could be explained by the wastewater treatment process since organic matters that are easy to assimilate were removed during secondary biological treatment [11].

The results of BDOC and AOC content tests in the analyzed water samples were compared with the biostability threshold value proposed by LeChevallier et al. [33] equal to 0.05–0.1 mg L^{-1} and the more strict value given by van der Kooij [34] and Weinrich et al. [35] amounted to 0.01 mg L^{-1}. Among the analyzed samples, 75% met the biostability term for BDOC and 65% for AOC. The majority of authors use for health risk assessment the assay of specific pollutants, most commonly organic, that predominate in drinking water of a given country. Tabtong et al. [36] conducted studies to investigate the presence of perfluoroalkyl substances in tap water and to assess their health risks.

Wang et al. [37] proposed the multi-pathway risk assessment (assessed through oral ingestion, dermal absorption, and inhalation exposure to drinking water) which was used to assess the cancer risk and the hazard index of trihalomethanes and haloacetics.

The obtained results indicate that the analysis of BDOC and AOC content can therefore be used for risk assessment in accordance with the new Polish regulation. The results obtained from the above research may be a starting point for further analyses of other contaminants appearing in the water supply network. The obtained results can be used to

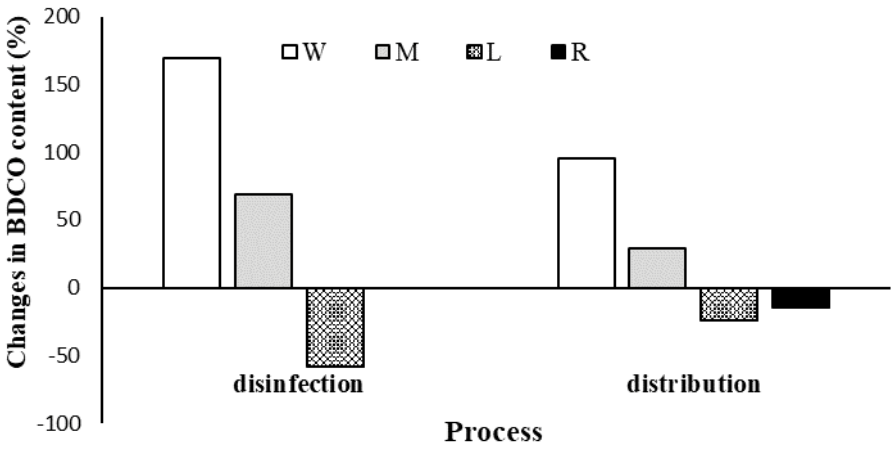

Fig. 3. Changes in BDOC content after the disinfection and distribution process.

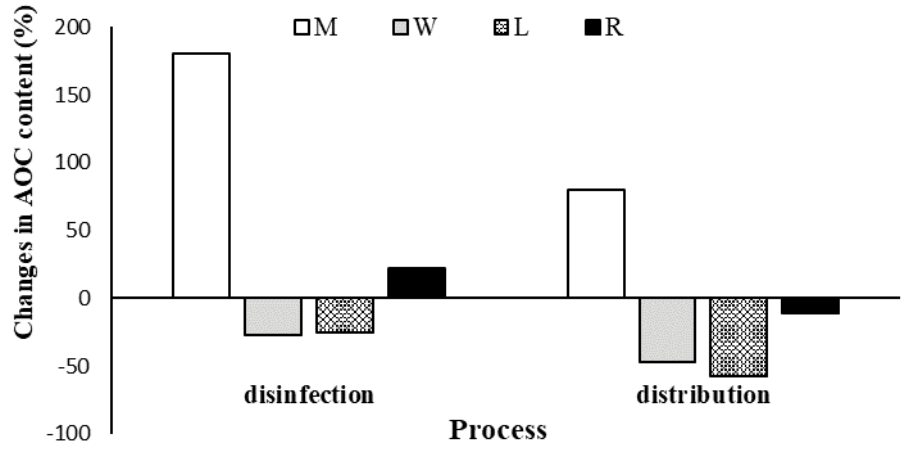

Fig. 4. Changes in AOC content after the disinfection and distribution process.

plan and make decisions regarding health risks. However, it should be taken into consideration that random studies do not solve many of the related problems of WSP implementation, so data must be seen in a somewhat historical context [20]. The scope of drinking water research should include a comprehensive qualitative analysis of the impact of culture on WPS implementation and important insights for practitioners. WSP implementation should be perceived globally, taking into account not only analyses of selected indicators and contaminants in drinking water, but also the management structures specific to countries with different incomes, including for example the tensions between water supply and water quality; the influence of professional subcultures (engineers and water quality scientists) on risk management initiatives. The critical importance of the collection and management of systemic knowledge during the development of the WSP is also important.

4. Summary

Determination of biodegradable organic matter is not a parameter regulated by law both in Poland and in the world, although it is generally known that the disintegration of disinfectants is directly related to an increase in BDOC. The obtained results indicate that the analysis of BDOC and AOC in waters intended for consumption may be a starting point for further analyses of other contaminants appearing in the water supply network. The research results can be used for planning and making decisions regarding the health risk of water intended for consumption. Evaluation of the content of BDOC and AOC as determinants of water biological stability may constitute a new concept for assessing the risk of microbiological hazards according to the implementation of WSPs.

Therefore, it is recommended to search for solutions that reduce the content of biodegradable organic carbon forms. The most commonly used method of removal of biodegradable organic substances from water is the biofiltration process preceded by water ozonation. This process removes the fraction of organic substances characterized by high reactivity toward disinfectants, which results in a decrease in water demand for the disinfectant and low content of disinfection by-products. However, final disinfection used after the biofiltration process creates additional amounts of BDOC. This means that during water filtration through biologically active beds, precursors of biodegradable organic substances are not fully removed. Therefore, further research is justified in order to develop methods to reduce the content of BDOC and AOC in water or alternative techniques for disinfection not generating AOC or BDOC.

Disinfection processes used in the analyzed WTPs do not ensure microbiological safety in the water at the consumer tap. During the distribution process, secondary microbial contamination of water occurs. BDOC and AOC content research can be used to assess the risk of secondary microbial development and can be used to plan and make decisions about health risks.

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