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EVALUATION OF ADSORPTION PERFORMANCE DURING FLOOD WATER PURIFICATION

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ABSTRACT: The purpose of this study was to evaluate the applicability of online flow cytometry for assessing the adsorption process in surface water treatment. The research was conducted under real operating conditions at a plant treating up to 100,000 m³/day using coagulation, sedimentation, filtration, ozonation, adsorption (on WG-12 activated carbon), and disinfection. Daily water samples were collected from August to November 2024, including a period of raw water deterioration due to floodwater. Flow cytometric analysis was performed online every 30 minutes to determine microbial viability and activity. Findings revealed increased TOC removal efficiency with higher organic content, but also elevated microbial release from the adsorption bed during peak contamination. Flow cytometry effectively distinguished between microbial activity levels and responded faster than traditional turbidity monitoring. This method offers practical benefits for real-time water quality control and disinfection management. The study demonstrates the originality and value of integrating online cytometry into adsorption process monitoring in water treatment.

KEYWORDS: adsorption, flood water, flow cytometry, water treatment, activated carbon

Introduction

The observed climate change is causing increasingly large areas of the world to experience water scarcity (Huang et al., 2021), which in turn leads to the abstraction, treatment, and consumption of water from various sources, including saline and rainwater (Alim et al., 2020). At the same time, these climate changes are resulting in more frequent extreme weather events, including heavy rainfall and floods (Radovanović et al., 2023). It is not always possible to capture and utilise such waters due to their volume and composition (Si et al., 2022), which can lead to an inability to provide water of suitable quality to people and may cause sanitary issues.

One of the main reasons for this is the significant pollution of floodwaters (Lim & Foo, 2021). The greatest threat from floodwater abstraction is its high contamination with microorganisms, including pathogenic ones (Mishra et al., 2021). Such water is characterised by very high turbidity and intense colouration (Ponting et al., 2021). Due to the serious health risks posed by floodwater contamination, the treatment of such water is very challenging from technical, technological, and operational perspectives. It is necessary to ensure the maximum effectiveness of individual water treatment processes within the constraints of existing infrastructure.

Flood-related deterioration in water quality mainly affects surface water, although groundwater is also susceptible to pollution infiltration through the soil. Significant degradation of groundwater composition during floods was reported by Rowles et al. (2020), with contamination primarily involving the presence of microorganisms such as Escherichia coli. In the case of surface water abstraction, in addition to microorganisms, floodwaters have been found to contain elevated concentrations of organic substances (Li et al., 2021) and heavy metals (Yang et al., 2024).

The greatest challenge in treating flood-affected surface water lies in intensifying unit treatment processes, particularly for the removal of organic matter. Therefore, during floodwater treatment, the optimisation of coagulation and adsorption processes (most commonly used for surface water treatment) is essential, as these processes are capable of removing the key contaminant groups that pose the greatest threat to human health.

In terms of coagulation, it is possible to improve the removal efficiency of organic matter by increasing the coagulant dose or changing the type of coagulant used (Rosińska & Dąbrowska, 2021). In the cases of significant water quality deterioration, it is common to apply two or more coagulants simultaneously. On the other hand, the use of adsorption processes during floodwater treatment significantly enhances water purification efficiency (Dao et al., 2021).

In surface water treatment systems that do not include an adsorption process, powdered activated carbon is often applied during flood events to improve water treatment effectiveness (Mahmud, 2024). This method is also used to support systems that already use adsorption through filter media. Managing this process during floods is extremely difficult, as technical and operational constraints often prevent an increase in the contact time between water and carbon, which is a key factor in process efficiency (Harja et al., 2022).

In situations involving the abstraction and treatment of highly contaminated waters, including floodwaters, a critical aspect is the level of microbiological contamination, which poses a significant health risk to water consumers (Su et al., 2024). Therefore, monitoring the abundance of microorganisms in treated water constitutes an important element in ensuring the safety of water supply systems. This consideration has led to the increasing application of online monitoring methods for microbiological water quality parameters. An example of such a method is online flow cytometry, which is based on flow cytometric measurements and enables the acquisition of results at 15-minute intervals (Besmer et al., 2016). The use of online methods for monitoring microbiological contamination allows for the optimisation of individual treatment processes and entire technological systems, particularly under conditions of frequent and rapid changes in water quality.

However, there is a lack of clear information regarding the assessment and management of this process during floodwater treatment, as well as the identification of parameters that could be used to evaluate its performance. There is currently a lack of definitive information on the extent of water contamination during sudden deteriorations in treated water quality, particularly following preliminary treatment steps such as coagulation and filtration. This gap is largely due to the fact that water treatment plants are often not operational during flood events, limiting data collection. Consequently,

DOI: 10.34659/eis.2026.98.3.1225

most available information pertains to the quality of raw water. This results in a scarcity of knowledge regarding the behaviour and performance of adsorption processes, the potential for process optimisation, and the mitigation of microbiological contamination in treated water during flood-induced raw water surges.

Therefore, it was justified to conduct a study aimed at assessing the effectiveness of the adsorption process during floodwater treatment and identifying parameters that could serve as a basis for such an assessment, for example, total cell count or turbidity.

The study aimed to assess the quality of water entering adsorption filters, evaluate adsorption efficiency and influencing factors, and explore the potential of **online flow cytometry** for monitoring and managing the process.

Based on this, the following research hypotheses were formulated:

- Online flow cytometry enables the management of the adsorption process during the treatment of flood-affected waters.
- The efficiency of the adsorption process increases with the level of contamination in the water undergoing adsorption.

Research methods

Research on the applicability of online flow-cytometric measurements for assessing the adsorption process was conducted under real conditions at a surface water treatment plant with a capacity of up to 100,000 m^3/day located in the south-western part of Poland, which was flooded in autumn 2024. The water is treated through coagulation with sedimentation, filtration, ozonation, adsorption, and disinfection processes.

The subject of the study was water samples taken before and after the adsorption process, which was carried out using rapid gravity filters filled with WG-12 activated carbon, the characteristics of which are presented in Table 1. The height of the carbon bed was 1.5 meters. The contact time between the water and the activated carbon depended on the plant's current capacity and ranged from 18 to 23 minutes.

During the study period, the activated carbon was characterised by partial exhaustion of its sorption capacity, as it had been operated for 10 months to 4 years, depending on the filter unit. The adsorption filters are backwashed every 40 days using water and air. The backwashing procedure includes a 5-minute air backwash followed by a 15-minute water backwash. The ozone dose applied before the adsorption process is adjusted to the level of contamination of the influent water and most often does not exceed 2 g O_3/m^3.

During the flood period, in order to ensure adequate quality of treated water and to increase the efficiency of unit processes, the plant capacity was reduced. As a result, the contact time between the treated water and the activated carbon was extended to 20–30 minutes, and the ozone dose was increased to a range of 2.17–4.10 g O_3/m^3. The frequency of filter backwashing was also increased from once every 40 days to once every 5 days.

Water samples were collected daily from August to November 2024, during which the quality of the raw water significantly deteriorated due to the intake of floodwater.

In the water samples, measurements were performed for pH, colour, turbidity, UV_{254} absorbance, total organic carbon, and counts of indicator microorganisms (E. coli, Clostridium perfringens, Enterococci), as well as the total number of psychrophilic and mesophilic microorganisms. Samples were collected once daily. Additionally, during the study period, online analysis of microbial counts was conducted using flow cytometry.

All water quality analyses were performed in accordance with applicable Polish standards (Table 2).

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Table 1. Parameters of fresh WG-12 activated carbon

No.	Parameter	Unit	Value
1.	Bulk density	g/L	470
2	Volatile content	%	1.50
3	Ash Content	%	11.6
4.	Specific Surface Area	m^2/g	968
5.	Iodine Number *	mg/g	1014
6.	CTC –adsorption CCl_4	%	62.3
7.	<0,5 mm subfraction content	%	0.0
8.	Mechanical strength	%	97.3

* parameter commonly used for adsorptive capacity assessment

Table 2. Compilation of the analytical methods used

Parameter	Unit	Standard	Measure method
Turbidity	NTU	PN-EN ISO 7027-1:2016-09	Turbidimetric method
Color	g Pt/m^3	PN-EN ISO 7887:2012, met.C	Spectrophotometric method
pH	-	PN-EN ISO 10523:2012	Potentiometric method
Absorbance UV_{254}	m^{-1}	PN-84/C-04572	Spectrophotometric method
Total organic carbon (TOC)	g C/m^3	PN-EN 1484:1999	Thermal method
Total microorganism number (TNM) psychrophilic	jtk/1mL	PN-EN ISO 6222:2004	Plate method – depth culture
Total microorganism number (TNM) mesophilic	jtk/1mL	PN-EN ISO 6222:2004	Plate method – depth culture
E.coli bacteria	jtk/100 mL	PN-EN ISO 9308-2:2014-06	NPL method (Colilert – 18)
Clostridium perfringens (including disputes)	jtk/100 mL	PN-EN ISO 14189:2016-10	Membrane filtration
Intact cell count (ICC)	cells/mL	Flow cytometry	On-line
HNAC*	cell/mL	Flow cytometry	On-line
LNAC**	cell/mL	Flow cytometry	On-line

* number of cells with high activity of nucleic acids; ** number of cells with low activity of nucleic acids

The total number of live cells and the counts of live cells with high and low nucleic acid activity were measured using Cyber-Green and pyridine iodide dyes, which were dosed under flow conditions. Measurements were taken every 30 minutes and averaged over 24 hours for interpretation. Measurements were carried out using a BactoSense CORE flow cytometer bNovate Technologies SA in Swissland (Figure 1). For cytometric analyses, water samples were taken from the pipeline supplying water to the carbon filter, after the ozonation process.

Measurements using the online cytometer are based on the operating principle of flow cytometry with the use of propidium iodide and SYBR Green as fluorescent dyes. Measurements were performed every 15 minutes and enabled the determination of the total number of cells, as well as cells with low and high nucleic acid activity, i.e. cells with low and high proliferation activity.

This allowed for the assessment of the usefulness of this measurement method in evaluating the course and biological activity of the adsorption bed.

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Figure 1. Flow cytometer

Results of the research

In the analysed water treatment plant, the water flowing into the carbon filters is characterised by a low level of contamination and little variability in water quality parameters throughout the year. However, during the intake of floodwaters, an increase in contamination levels was observed, particularly regarding organic pollution and the number of microorganisms (Table 3). A significant increase in contamination during floodwater intake was also reported by Teplykh et al. (2024), who identified the presence of microorganisms as the greatest threat to the treatment of floodwaters.

In all water samples taken after the adsorption process, a decrease in pH was observed, which may indicate the release of CO_2 as a result of the decomposition of organic substances by microorganisms living in the adsorption bed. This hypothesis is supported by the research of Goel et al. (2021), which showed that the decrease in pH was proportional to the reduction in the content of the biodegradable fraction of organic substances.

The course of biodegradation and adsorption of organic substances is evidenced by the observed decrease in UV_{254} absorbance (Figure 2) and total organic carbon in all water samples, regardless of the quality of water entering the carbon filters. Despite the inflow of water with increased organic content into the carbon filters during the flood, the content of organic substances and UV_{254} absorbance values after adsorption remained at a similar level. This may be due to the use of a higher ozone dose before the activated carbon filters and increased microbial activity resulting from higher oxygen content and other nutrient substrates (Dos Santos & Daniel, 2020). In the initial phase of floodwater inflow, an increase in UV_{254} absorbance was noted, which then stabilised at a level higher than that recorded before the flood.

However, in the case of organic carbon removal (TOC), no such trend was found, and the values of this parameter in post-adsorption water in all samples met the drinking water standards. A significant increase in the effectiveness of total organic carbon removal was noted, proportional to the increase in the parameter's value in water entering the carbon filters (Figure 3).

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Table 3. Ranges and average values of water quality parameters before and after adsorption during the flood period, as well as before and after that period

Parameter	Unit	Influent						Outfluent					
		Before and after flood			Flood			Before and after flood			Flood		
		min	max	aver.	min	max	aver.	min	max	aver.	min	max	aver.
Color	gPt/m^3	1.0	5.0	2.0	3.0	6.0	4.1	1.0	3.0	1.1	1.0	3.0	1.9
Turbidity	NTU	0.4	0.4	0.4	0.4	2.4	0.6	0.4	0.4	0.4	0.4	1.1	0.5
pH		7.0	7.7	7.5	7.0	7.2	7.1	7.0	7.6	7.3	6.8	7.2	7.0
TOC	gC/m^3	2.86	5.13	3.80	6.42	7.40	6.90	1.97	3.91	2.70	4.13	4.48	4.30
UV_{254}	m^{-1}	2.17	7.15	4.20	5.47	9.64	7.70	1.11	5.03	3.30	3.22	5.84	4.90
Group of coli	cfu/100 mL	0	5	0	0	61	11	0	58	6	4	150	57
E.coli	cfu/100 mL	0	0	0	0	0	0	0	0	0	0	0	0
Enterococci	cfu/100 mL	0	0	0	0	0	0	0	0	0	0	0	0
Clostridium perfringens	cfu/100 mL	0	0	0	0	0	0	0	0	0	0	0	0
TNM psychrophilic	cfu/ mL	1	260	94	57	990	345	1800	15000	6537	2700	9600	5192
TNM mesophilic	cfu/ mL	1	10	3	2	95	20	2	650	201	59	570	268
ICC	cell/mL	NA	NA	NA	NA	NA	NA	1617	460667	258692	208580	239663	226324
HNAC	cell/mL	NA	NA	NA	NA	NA	NA	18	158360	96979	94080	128670	117293
LNAC	cell/mL	NA	NA	NA	NA	NA	NA	1583	304327	161492	103730	114490	109023

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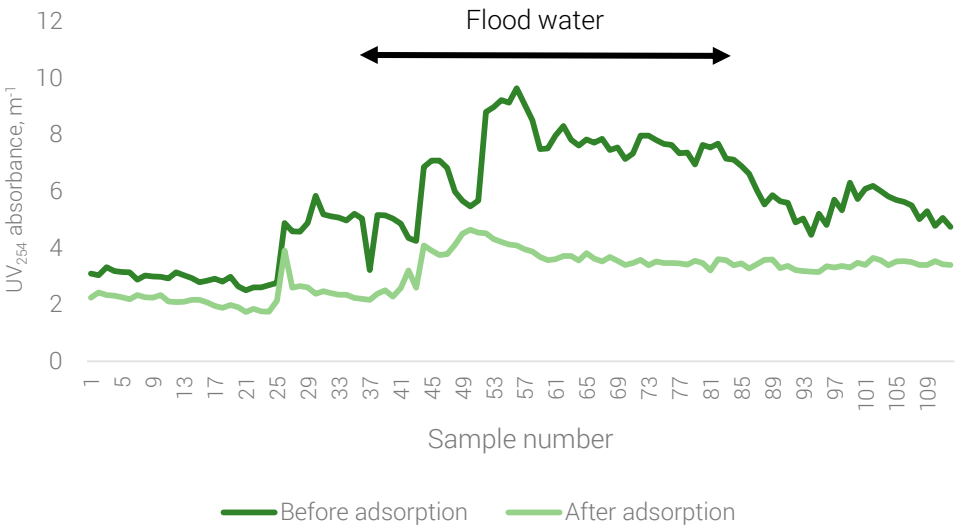

Figure 2. Variability of UV_{254} absorbance before and after adsorption

This means that with an approximately 100% increase in the organic substance content in the water entering the adsorption process, it is possible to achieve higher adsorption efficiency of organic substances by the biologically active bed. On the other hand, the research by Wang et al. (Wang et al., 2022) showed that the effectiveness of removing both TOC and UV_{254} absorbance depended less on the values of these parameters in the inflowing water and more on the properties of the organic substances themselves. The differing results may stem from the constant turbidity of water undergoing adsorption in their study, which was not the case when treating floodwaters. During the floodwater inflow period, turbidity increased from 0.4 NTU to 2.4 NTU. The resulting suspended solids in the water feeding carbon beds required more frequent backwashing of the filters, while also increasing the adsorption surface – due to higher concentrations of residual aluminium after coagulation.

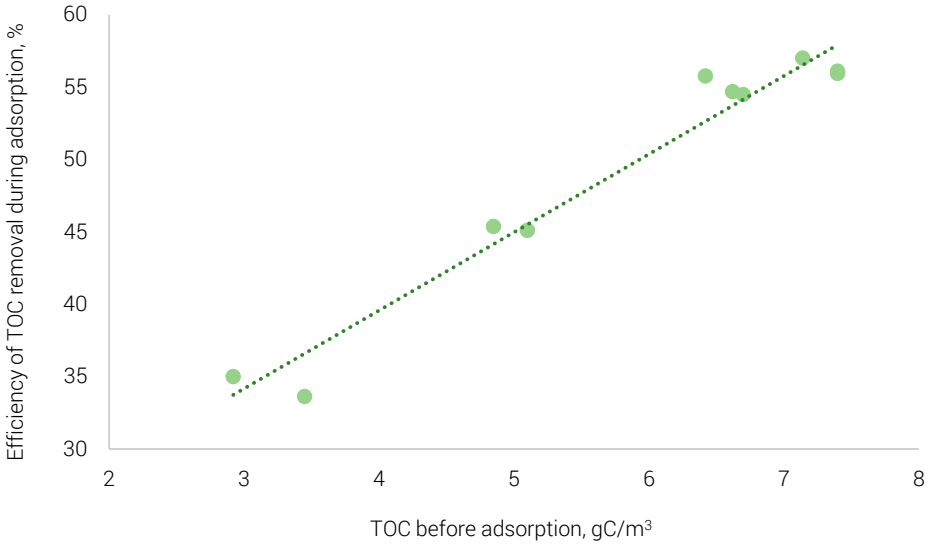

Figure 3. Relationship between TOC concentration in influent and efficiency of TOC removal (ηTOC=5.4016*TOC+17.974; R=0.97)

Turbidity is commonly employed as an indicator for assessing water contamination, including microbiological pollution (Steadmond et al., 2023). However, numerous studies have reported that no straightforward correlation exists between turbidity and microbial abundance, particularly in

DOI: 10.34659/eis.2026.98.3.1225

treated waters with low turbidity. As a result, cytometric techniques are increasingly being applied to evaluate microbiological contamination, as they provide a direct measurement of the total number of cells present in the water (Dowdell et al., 2024). This approach enables precise monitoring of changes in microbial populations, facilitating more effective management and assessment of the performance of individual water treatment processes.

The efficiency of removing organic substances and reducing UV_{254} absorbance depends on the characteristics of the organic matter present in the treated water. As demonstrated by Piai et al. (2024), in the case of treating water with a high organic carbon content and high absorbance, the initial stage of the process is characterised by a very effective reduction of UV_{254} absorbance and a very rapid exhaustion of the sorption capacity of the adsorption bed. In general, UV_{254} absorbance is used to assess the breakthrough point of the adsorption bed, and its online measurement is applied for process control and management (Anumol et al., 2015). During the study period, especially during the deterioration of the quality of water entering the carbon filters, an increase in the number of psychrophilic and mesophilic bacteria in the water after adsorption was observed (Figure 4). The washing out of microorganisms from the surface of the activated carbon indicates their intense growth. The same trend was noted by Lu et al. (Lu et al., 2022). Among the bacteria, both before and after adsorption, psychrophilic bacteria dominated, constituting over 90% of all bacteria in most water samples. This indicates that this parameter can be used to assess biological activity.

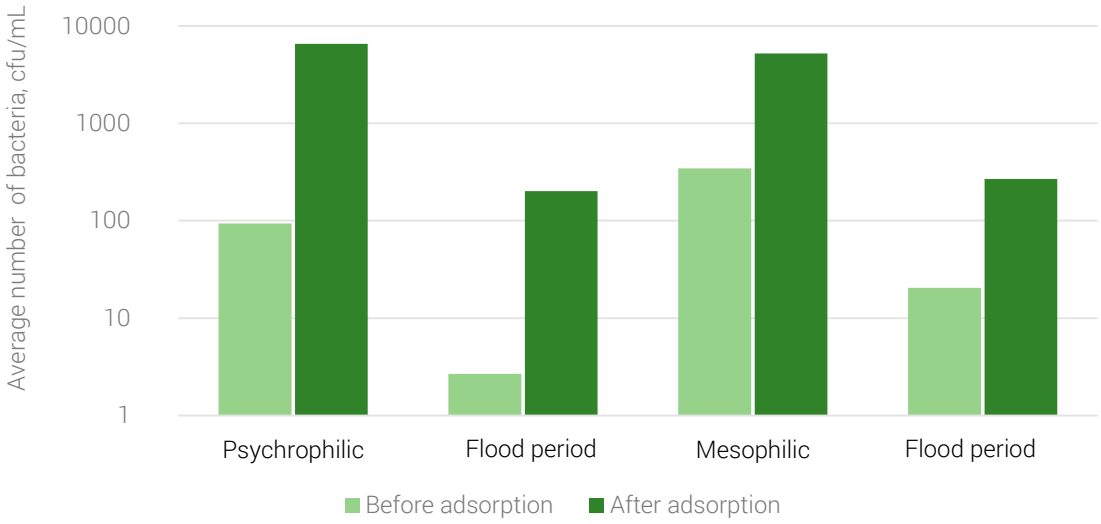

Figure 4. Average number of bacteria before and after adsorption

The number of these bacteria in the filtrate was very high during the period of deteriorated water quality and slightly decreased after the water quality stabilised. Meanwhile, the total number of cells, measured online, significantly decreased after stabilisation of water quality (Figure 5). It is also worth noting that no correlation was found between the total cell count and the number of psychrophilic and mesophilic bacteria, as has already been confirmed in many studies (Wilkinson, 2018). However, the significant change in their number indicates the washing out of microorganisms accumulated in the bed after floodwater flow. This means that this parameter can be used to assess the performance of biologically active adsorption beds. However, this requires long-term calibration and comparative analysis of both assessment methods.

To evaluate the course of adsorption, the proportion of cells with high and low ribonucleic acid activity in the water after adsorption can be used. The presence of bacteria with high nucleic acid activity indicates a significant potential for cell division and colony and/or biofilm development. This means that a higher proportion of HNAC bacteria in water quality monitoring may indicate a risk of secondary microbial growth, whereas a decrease in HNAC proportion in ICC reflects limited microbial activity in the water (Claveau et al., 2024).

Variability in this proportion (Figure 6) reflects both the quality of the incoming water and the level of microbiological contamination. During the floodwater inflow, cells with high activity consti-

DOI: 10.34659/eis.2026.98.3.1225

tuted the majority – about 55%. After the flow of highly contaminated water and the subsequent stabilisation of its quality, the proportion of low-activity cells exceeded 90%. This indicates that under stable operating conditions, low-activity bacteria dominate in the bed, and their abundance is proportional to the number of psychrophilic bacteria.

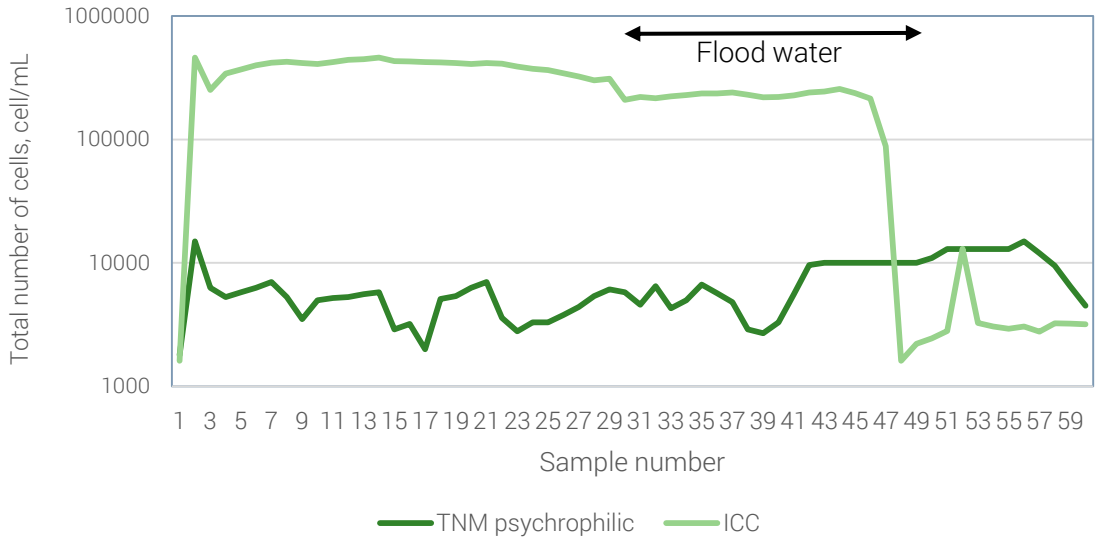

Figure 5. Variability of total number of cells and psychrophilic bacteria in effluent of biologically activated carbon (BAC)

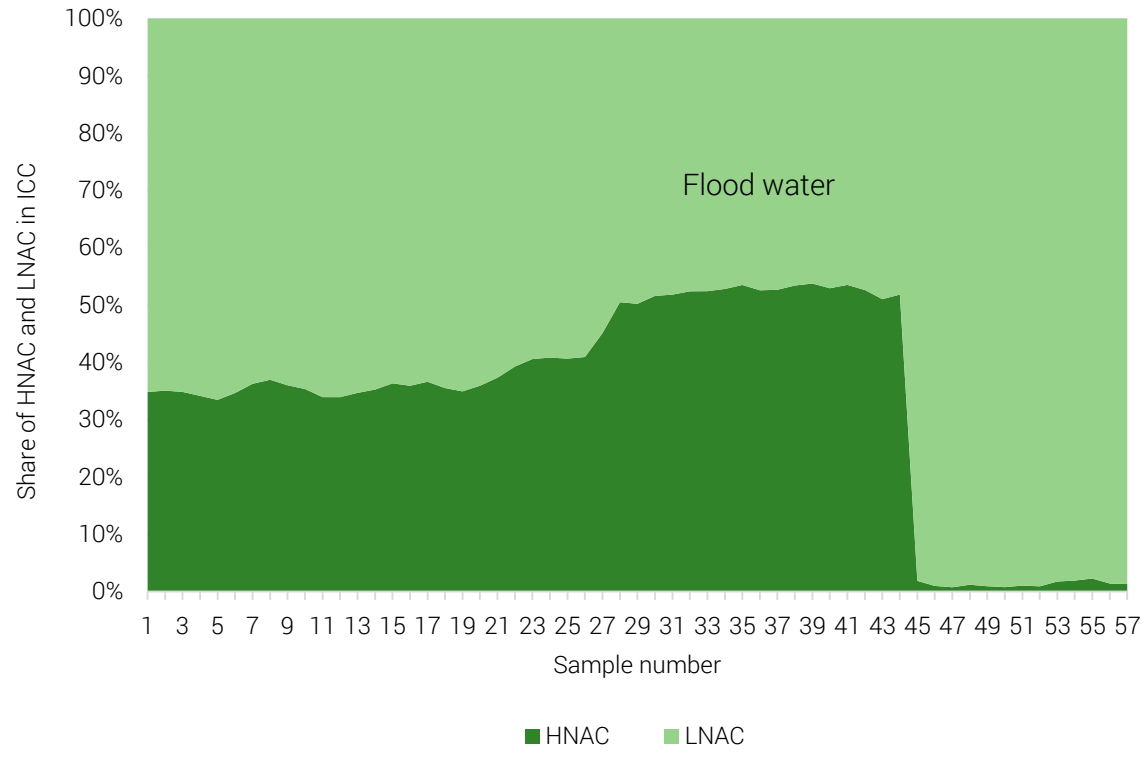

Figure 6. Share of HNAC and LNAC in water after adsorption

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Conclusions

The results of the study showed that:

- the use of online monitoring of water quality parameters is crucial for managing water treatment during sudden and short-term deteriorations in water quality, such as those occurring during floods.
- floodwater treatment requires adjustments to the operational parameters of the adsorption process, in particular extending the contact time and increasing the frequency of backwashing of adsorption filters.
- during the period of floodwater intake, water with nearly twice the organic matter content flowed into the adsorption filters,
- the efficiency of TOC removal increased with the rising content of organic matter in the water entering the adsorption process,
- during the treatment of water with the highest level of contamination, a very large number of microorganisms were released from the adsorption filters into the treated water,
- flow cytometry can be used to assess the level of microbiological contamination, especially the proportion of microorganisms with low and high activity,
- raw water turbidity during the flood did not change proportionally to the TOC content or microorganism count; therefore, during periods of significant water quality deterioration, it cannot be used to manage the adsorption process,
- online cytometry, due to its near real-time results, is a valuable tool for evaluating the adsorption process, particularly for selecting the appropriate disinfectant dose after this stage.

Acknowledgements

The scientific research was funded by the statutory subvention of Wroclaw University of Science and Technology (Faculty of Environmental Engineering) and Czestochowa University of Technology (Faculty of Infrastructure and Environment).

The contribution of the authors

Conceptualization, M.W., A.R. and M.K.K. ; literature review, A.R., M.O.K. and H.U.K..; methodology, A.S.P., M.W..; formal analysis, M.W., A.R., M.K.K., H.U.K., M.O.K. AND A.S.P.; writing, M.W., A.R., M.K.K., H.U.K., M.O.K. AND A.S.P.; conclusions and discussion, M.W., A.R. and M.K.K.

The authors have read and agreed to the published version of the manuscript.

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DOI: 10.34659/eis.2026.98.3.1225

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OCENA WYDAJNOŚCI ADSORPCJI PODCZAS OCZYSZCZANIA WODY POWODZIOWEJ

STRESZCZENIE: celem pracy była ocena skuteczności procesu adsorpcji podczas uzdatniania wód powierzchniowych o pogorszonej jakości, w tym wód powodziowych, z wykorzystaniem pomiarów cytometrii przepływowej online. Badania przeprowadzono w rzeczywistych warunkach stacji uzdatniania wody o wydajności do 100 000 m³/dobę. Próbki pobierano przed i po procesie adsorpcji prowadzonej na filtrach węglowych z węglem aktywnym WG-12. Analizowano parametry fizykochemiczne i mikrobiologiczne, w tym liczebność mikroorganizmów przy użyciu cytometrii przepływowej. Wykazano, że pomimo poprawy skuteczności usuwania materii organicznej, intensywne zanieczyszczenie skutkowało uwalnianiem drobnoustrojów ze złoża. Cytometria przepływowa okazała się przydatnym narzędziem do monitoringu biologicznej aktywności złoża oraz oceny potrzeby dozowania środka dezynfekującego. Badania potwierdziły, że cytometria przepływowa może być skutecznym narzędziem wspierającym zarządzanie procesem adsorpcji w czasie rzeczywistym, zwłaszcza podczas gwałtownego pogorszenia jakości wody.

SŁOWA KLUCZOWE: adsorpcja, woda powodziowa, cytometria przepływowa, uzdatnianie wody, węgiel aktywny

DOI: 10.34659/eis.2026.98.3.1225