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Influence of Sitkówka sewage treatment plant on the Bobrza River water quality

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Abstract

The paper presents an analysis of 20 physicochemical elements in the Bobrza River water sampled above and below the treated sewage discharge point. Sitkówka mechanical and biological sewage treatment plant with a value of 289 000 People Equivalent discharges on average 51 000 m^3 of treated sewage daily, which makes up 29% of mean daily flow in the Bobrza River. On the basis of hydrochemical analyses it was stated that the discharge of treated sewage led to worsening of 18 out of 20 studied water quality indices in the Bobrza River. In the river water below the sewage discharge statistically significantly higher values of electrolytic conductivity, dissolved solids, calcium, magnesium, sodium and potassium were registered. A decrease in dissolved oxygen content in the water and increase in its electrolytic conductivity caused a change of water quality class in the Bobrza River from the maximum potential to potential below good. On the other hand, increase in concentrations of dissolved solids and sulphates caused a change of the water class from the maximum potential to good potential. Statistical factor analysis (FA) made possible a reduction of a set of 20 physicochemical elements to four mutually orthogonal factors explaining 95% (above the treatment plant) and 96% (below the treatment plant) of the internal structure of primary data. The first factor is connected with point source pollution (sewage discharge), the second describes oxygen conditions in water, the third results from seasonality and is responsible for the pollutants from natural sources, whereas the fourth factor has not been unanimously defined yet.

Key words: *environmental monitoring, pollutants, sewage discharge, water quality*

INTRODUCTION

Quantitative and qualitative protection of water resources is the imperative assumption of the European Union Framework Water Directive, which obliges the member states to achieve good quality of waters [Directive 2000/60/EC; HALLIDAY *et al.* 2014; WHO 1993]. Changes of water quality in receiving waters caused by discharging treated sewage to surface waters are the worldwide problem [CHMIELOWSKI *et al.* 2016; COTMAN *et al.* 2004; GRAHAM *et al.* 2010; MAKOWSKA 2014; POLICHT-LATAWIEC 2012; SCANES 2011].Water pollution is to a considerable extent caused by nutrients, which together with sewage find their way to the aquatic environment [JÓŹWIAKOWSKI, MARZEC 2008; KANOWNIK, POLICHT-LATAWIEC 2016; NEVEROVA-DZIOPAK, CIERLIKOWSKA 2014; PANNO *et al.* 2008; RAJDA, KANOWNIK 2006]. Assessment of water and sewage management system is carried out in order to indicate the effect of sewage discharged from a treatment plant on surface watercourses [BATKOWSKI 2014; KRÓLAK *et al.* 2011; KUMAR *et al.* 2012; MARTÍNEZ BUENO *et al.* 2012; PIEKUTIN 2008].

Progressive economic and industrial development leads to gradually higher standards of household sanitation systems, which increases the amount of sewage supplied to municipal treatment plants, whose task involves its treatment ensuring that the cleaned sewage introduced to water ecosystem would not affect negatively its ecological and chemical state [KANOWNIK *et al.* 2016]. Therefore, the receiving waters must be selected so, that supplying a pollutant load would not exceed some determined sewage volume, which might limit water self-purification process, that is the next stage of sewage treatment [HOLGUIN *et al.* 2013; KANOWNIK, RAJDA 2011]. Increase in produced sewage volume causes that sewage treatment plants are being constructed all the time or old sewage treatment plants and sewer system are being modernized. Therefore, research conducted on the effect of treated sewage on water quality in the receiving waters is necessary to fulfil the requirements stated in Directive 91/271/EWG and the provisions of the Accession Treaty. The National Programme for Municipal Waste Water Treatment (NPMWWT) has been implemented in Poland since 2010 [KAŁEK, PIASKOWSKI 2010; POLICHT-LATAWIEC *et al.* 2016; SZAFLIK *et al.* 2014; WERLE, WILK 2010]. It is also associated with the assumptions of the European Union water policy where the basic issues are the sustainable development of member states concerning the political, economic and social activities at simultaneous maintaining the natural balance and stability of fundamental natural processes [Directive 2000/60/EC].

Pursuant to water law, the territory of Poland was divided into water regions and basin areas, which were characterized in terms of the impact of human activities [DMOCHOWSKA, DMOCHOWSKI 2011; DOMAGAŁA *et al.* 2010], economic analysis of water use from the perspective of the balance of costs for water services. It has been forecasted, that establishing the permissible values for pollutant emission and their environmental quality standards would lead to reducing pollutants at their source [COPPENS *et al.* 2015; JELIĆ *et al.* 2011; MIATKOWSKI, SMARZYŃSKA 2014; Rozporządzenie MŚ… 2014; SADECKA *et al.* 2010].

The aim of the paper has been determining the changes of water quality in the Bobrza River caused by treated sewage discharge from Sitkówka mechanical-biological treatment plant, serving mainly the city of Kielce. Analysis of 20 physicochemical elements of the Bobrza River water sampled above and below the treated sewage discharge point was conducted in the paper. The sources of river feeding and the origin of the substances influencing the river water composition were identified.

MATERIAL AND METHODS

STUDY AREA

The studied section of the Bobrza River catchment is administratively located in Świętokrzyskie province, Kielce county and Sitkówka-Nowiny district, in Wola Murowana (Fig. 1), whereas in terms of physicogeographical region, in the Kielce upland macroregion, within the Świętokrzyskie Mountains mezoregion [KONDRACKI 2013]. The Bobrza River (4th order) is the right bank tributary to the Czarna Nida, flowing into the Nida River. The spring of the Bobrza River is situated at 370 m a.s.l. The river flows from its source heading west, between Tumlin Hills and Suchedniów-Oblęgorek Landscape Park situated on Suchedniów Plateau, then it forms a gorge through the Oblęgorek Range by Bobrza village and turns to the south. The river forms a next gorge between the Zgórskie Range and Posłowickie Range and flows into the Czarna Nida on the Szydłów Plateau, at the south-eastern edge of Chęciny-Kielce Landscape Park, near Wolica village at 217 m a.s.l. The total Bobrza River length is 50.7 km, average channel slope 3.24‰. The Bobrza headwaters were classified to abiotic type 5 as upland silicate stream with a fine-grained substrate, whereas the analysed river reach from Ciemnica to the its mouth as type 8 upland, silicate-western river [KZGW 2014]. The catchment area to the sewage discharge point from Sitkówka treatment plant is 335 km^2.

Fig. 1. Location of measurement and control point; source: own elaboration

A hydrometric station of the Institute of Meteorology and Water Management (IMGW) closing the Bobrza-Słowik catchment is situated on the river (308 km^2). The Bobrza River course reveals a clear seasonal variability. The highest average monthly unit runoff for the years 1961–2000 occurred in March – 10.2 $dm^3 \cdot s^{-1} \cdot km^{-2}$ and the lowest in October – 3.8 $dm^3 \cdot s^{-1} \cdot km^{-2}$ [CIUPA *et al.* 2010]. Average annual runoff value was 6.1 $dm^3 \cdot s^{-1} \cdot km^{-2}$, i.e. an average flow in the place of sewage discharge is 2.04 $m^3 \cdot s^{-1}$.

Sitkówka sewage treatment plant has been operating since 1974. It covers the area of 21 hectares and has 65 facilities. In the years 2008–2011 the treatment plant was modernized to improve the efficiency of nutrient (biogenic compounds) removal and installation for thermal utilization of sewage sludge was constructed. Sewage is supplied to the treatment plant gravitationally from a sewer distribution system of Kielce city, Sitkówka-Nowiny district and Masłów district by means of Pakosz-Sitkówka main collector with a diameter of 1600/1800 mm. The treatment plant receives also sewage supplied by gully emptier fleet from the unsewered areas. Its mean daily throughput is 51 000 m^3, which constitutes as much as 29% of the average daily water flow in the Bobrza River. The maximum daily throughput is 58 000 m^3 at the loading of 289 000 people equivalent (PE).

Sewage inflowing from the sanitary sewer to the treatment plant are pre-treated mechanically on bar screens and in aerated grit chambers with separate grease trap chamber. Subsequently, sewage is directed to four primary settling tanks, from which the primary sludge is passed to the residual sludge pumping station. In the biological part of the treatment plant, predenitrification chambers, to which the activated sludge is recirculated, remove the nitrate and oxygen from the recirculated sediment, and in the dephosphatation chambers the phosphorus contained in the cells of the bacterial suspension of activated sludge is released. Subsequently, the final removal of pollutants from the sewage occurs in a biological reactor with separate denitrification and dephosphatation chambers. Sewage together with activated sludge flow to four secondary settling tanks, from which after clarification they outflow to the Bobrza River. Sludge with screenings, sand and grease is subjected to thermal utilization in the treatment plant [NEVEROVA-DZIOPAK, CIERLIKOWSKA 2014]. The maximum daily amount of sludge incinerated at the Thermal Sewage Sludge Removal Station is 88.8 $Mg \cdot d^{-1}$, whereas its hourly efficiency is 740 kg of sludge dry mass. Biogas produced in the sludge processing drives generators, while generated electricity and heat are used for the sewage treatment plant needs [Wodociągi… 2010].

WATER QUALITY PARAMETERS

Hydrochemical analyses of the Bobrza River water were conducted in 2014. Water samples were collected [ISO 5667-6:1997] on 8 dates, once a month, at four measurement-control points (Fig. 1): 1000 m (point 1) and 200 m (point 2) above the collector outlet from the treatment plant and about 100 m (point 3) and 500 m (point 4) below the treated sewage discharge. The following measurements were conducted on site: electrolytic conductivity was measured using CC-102 EC meter, water temperature, dissolved oxygen and degree of water saturation with oxygen by means of CO-411 oxygen meter, as well as total dissolved solids by means of TDS meter (HACH LANGE). In laboratory, total suspended solids were assessed by oven-dry method and concentrations of Ca^{2+}, Mg^{2+}, Na^+, K^+ and Fe (Fe^{2+} and Fe^{3+}) and Mn^{2+} ions by means of atomic absorption spectrometry (AAS) on Unicam SOLAAR 969 spectrometer. Five-day biological oxygen demand (BOD_5) was determined using Winkler method and chemical oxygen demand (COD-Mn) using titration method in $KMnO_4$. Concentrations of ammonium nitrogen ($N\text{-}NH_4^+$), nitrite nitrogen ($N\text{-}NO_2^-$) and nitrate nitrogen ($N\text{-}NO_3^-$), phosphate phosphorus ($P\text{-}PO_4^{3-}$) and chlorides (Cl^-) were determined using continuous flow colorimetric analysis on FIAstar 5000 apparatus, while sulphates (SO_4^{2-}) by precipitation method [Rozporządzenie MŚ… 2016a].

DATA PRETREATMENT

The Bobrza water quality class (small upland silicate-western river) was determined at measurement-control points in compliance with the Regulation of the Minister of the Environment on the methods of classification of the ecological status, ecological potential and chemical state of uniform parts of surface waters [Rozporządzenie MŚ… 2016b]. The results were elaborated using descriptive statistics, minimum and maximum values were determined, as well as arithmetical mean and median for individual indices. Cluster analysis was conducted to group the measurement – control points so that inside each of the identified groups, values of physicochemical elements were similar to each other. The analysis uses internal similarity and external dissimilarity. If clusters of points similar to each other exist, the structure may be presented as separate branches on a hierarchical tree (dendrogram). The distances between groups were estimated using Ward method, which bases on the analysis of variance and aims at minimization of the sum of squares of any two clusters. Statistical inference about the significance of differences of the physicochemical elements' (indices) values between the grouped measurement-control points (above and below the treated sewage discharge) was conducted using non-parametric U Mann Whitney test. The test was selected due to a lack of normality for a majority of analysed indices, according to the results of Shapiro-Wilk test and lack of equality of variance determined by Fisher-Snedecor test [STANISZ 2007]. Factor analysis (FA) was conducted to identify the feeding sources and origin of the substances shaping the physicochemical composition of the Bobrza River. The outliers were rejected at the initial stage of the analysis of physicochemical indices. The indices values which did not reveal the normality of distribution were subjected to normalization using transforming functions. Further lack of normality of the dataset led to a rejection from the analysis of BOD_5 and magnesium from the points above the sewage discharge. Due to the fact, that the analysed indices were expressed in different units, standardization of variables was conducted prior to the start of the analyses. Prepared dataset was subjected to factor analysis (FA) with factor rotation using varimax method, which reduces the ambiguity of interpretation. Owing to the rotation, each factor may be more easily identified with the variables (physicochemical elements), with which it is strongly correlated [LIU *et al.* 2003; SHERSTHA, KAZAMA 2007; SOJKA *et al.* 2008; WANG *et al.* 2013].

RESULTS AND DISCUSSION

The temperature of the Bobrza River water over the investigated period ranged from 5.7 (at point 1 – above the treatment plant) to 21.8°C (at point 4 – below the treatment plant). These values did not exceed the values permissible by the Minister of Environment Regulations of 2016 [Rozporządzenie MŚ… 2016b] – Table 1. Total suspended solids concentration fell within the range between 1 and 11.8 mg·dm^{-3} and its average value was on the level of 4.6 mg·dm^{-3} at the studied points both above (point 1) and below the treatment plant (point 4). Maximum concentration of suspended solids (11.8 mg·dm^{-3}) did not exceed the value required in the minister's regulation. In case of dissolved oxygen, only at point 4 (500 m below the discharge) its mean value 7.3 mg O_2·dm^{-3} was by 0.1 mg O_2·dm^{-3} lower than the value admissible by the minister for class II waters. The highest BOD_5 value (3.4 mg O_2·dm^{-3}) was noted above the sewage discharge at point 1 and did not meet the requirements for class II, whereas at the other measurement-control points these values were compliant with the limit values for class II waters. Mean concentration of COD-Mn along the whole length of the analysed watercourse stretch was similar and ranged from 9.1 to 9.5 mg O_2·dm^{-3}. Values of COD-Mn did not meet the ministry requirements for class II (Tab. 1). Concerning the electrolytic conductivity, the highest mean value (533 µS·cm^{-1}) was registered 100m below sewage discharge from the treatment plant and it caused that the potential of analysed waters was below good. A slight decreasing trend of *EC* value was observed at the next point 4, situated 500 m away and improvement of the water quality (class II). At the points above sewage discharge, low *EC* values, meeting the requirements for class I caused, that the watercourse waters were of the maximum potential. Concentrations of dissolved solids and sulphates measured during the investigations period above the discharge

Table 1. The range and average values of physicochemical indices and water quality class in the Bobrza River

Indicator	Range				Average				Limit values for class Rozporządzenie MŚ 2016	
	measurement-control point									
	above discharge		below discharge		above discharge		below discharge			
	1	2	3	4	1	2	3	4	I	II
Temperature, °C	5.7–21.3	6.5–21.3	7.3–21.6	7.0–21.8	13.5	13.3	13.9	14.0	≤22	≤24
TSS, mg·dm^{-3}	1.9–10.0	2.4–11.8	1.6–11.8	1–7.4	4.6	5.3	5.5	4.6	≤7.5	≤13.5
DO, mg O_2·dm^{-3}	4.5–10.8	4.3–10.9	3.9–10.4	3.8–10.2	8.2	8.1	7.4	7.3	≥7.5	≥7.4
OSD, %	63–102	65–107	58–104	61–105	86	88	83	85	–	
BOD_5, mg O_2·dm^{-3}	1.6–10.5	1.3–5.5	0.7–10.5	1.3–7.0	3.4	2.9	3.2	2.8	≤2.4	≤3.2
COD-Mn, mg O_2·dm^{-3}	6.3–12.9	6.1–13.4	5.8–12.8	6.0–12.5	9.5	9.1	9.3	9.2	≤6.9	≤7.3
EC, µS·cm^{-1}	166–498	174–504	204–744	202–766	371	389	534	490	≤404	≤493
TDS, mg·dm^{-3}	168–278	176–318	193–427	191–416	215	232	310	307	≤282	≤356
SO_4^{2-}, mg·dm^{-3}	25–52	28–71	18–66	20–73	35.6	38.1	47.9	45.4	≤45.0	≤80.5
Cl^-, mg·dm^{-3}	31–64	18–64	17–78	18–78	42.3	37.0	51.9	50.4	≤36.2	≤40.0
Ca^{2+}, mg·dm^{-3}	20–54	20–53	22–73	22–73	44.0	43.9	53.1	52.0	≤43.2	≤43.3
Mg^{2+}, mg·dm^{-3}	4.5–10.8	4.5–10.9	4.6–11.9	4.7–12.0	8.6	8.8	10.0	10.0	≤6.9	≤14
Na^+, mg·dm^{-3}	10–37	10–36	10–54	10–56	21	21	36	35	–	
K^+, mg·dm^{-3}	3.6–5.3	4.0–5.3	4.0–11.7	3.8–11.4	4.5	4.5	8.7	8.2	–	
P-PO_4^{3-}, mg·dm^{-3}	0.03–0.17	0.02–0.18	0.03–0.19	0.03–0.19	0.058	0.058	0.062	0.060	≤0.065	≤0.101
N-NH_4^+, mg·dm^{-3}	0.01–0.48	0.00–0.41	0.08–0.70	0.03–0.71	0.203	0.179	0.243	0.354	≤0.633	≤0.77
N-NO_2^-, mg·dm^{-3}	0.02–0.18	0.03–0.12	0.02–0.31	0.03–0.32	0.06	0.06	0.08	0.09	≤0.01	≤0.03
N-NO_3^-, mg·dm^{-3}	0.60–3.53	0.67–3.51	0.77–4.47	0.81–4.38	2.2	2.5	2.8	2.9	≤2.2	≤3.7
Fe, mg·dm^{-3}	0.33–2.07	0.02–1.72	0.18–1.42	0.15–2.10	0.92	0.68	0.49	0.71	–	
Mn^{2+}, mg·dm^{-3}	0.05–0.45	0.05–0.39	0.07–0.26	0.07–0.41	0.23	0.19	0.15	0.20	–	

quality class I – maximum potential; quality class II – good potential; does not meet the requirements of quality class II – below the good potential

Explanations: TSS = total suspended solids, DO = dissolved oxygen, OSD = oxygen saturation degree, BOD_5 = biochemical oxygen demand, COD-Mn = chemical oxygen demand, *EC* = electrolytic conductivity, TDS = total dissolved solids. Values on a white background – indicators are not included in the Rozporządzenie MŚ 2016b.
Source: own elaboration.

point were on the level of class I, whereas below the discharge increased values were observed, which caused that the waters were classified to class II. Mean concentrations of Cl^- at points 1, 3 and 4 exceeded permissible values stated in the minister regulations in force for class II. Only value noted at point 2, i.e. 37.0 $mg \cdot dm^{-3}$ was lower than permissible for class II. Mean calcium concentration registered during the period of research exceeded the limit value for class II. In case of magnesium its water concentrations were on the level of class II. Average values of phosphate phosphorus and ammonium nitrogen concentrations at all measurement-control points did not exceed the limit values for class I. On the other hand, mean concentration of nitrate nitrogen caused that water was classified to the potential below good. Its highest mean concentrations were registered in water below the treatment plant, respectively 0.08 and 0.09 mg $N\text{-}NO_2^- \cdot dm^{-3}$ (Tab. 1). Mean values of iron concentrations (Fe^{2+} and Fe^{3+}) during the period of investigations were as follows: at point 1 – 0.92 $mg \cdot dm^{-3}$, 2 – 0.68 $mg \cdot dm^{-3}$, 3 – 0.49 $mg \cdot dm^{-3}$ and at point 4 – 0.71 $mg \cdot dm^{-3}$. The highest value for manganese, 0.23 $mg \cdot dm^{-3}$ occurred at point 1 (Tab. 1).

Conducted cluster analysis allowed for the identification, among the investigated measurement-control points, of 2 groups of physicochemical water elements with similar values (the bond distance is less than 4). The first comprises the points above, whereas the second the points below sewage discharge from the treatment plant (Fig. 2). Comparison of the physicochemical indices values between the points above and below the treated sewage discharge points, conducted using non-parametric U Mann Whitney test, revealed that over the investigated period statistically significantly higher values of *EC*, TDS, Ca, Mg, Na and K occurred at the points below the treatment plant. The other analysed indices (the temperature, TSS, SO_4, Cl, $N\text{-}NH_4$, $N\text{-}NO_2$ and $N\text{-}NO_3$) were also higher in relation to the points above the treatment plant, but the differences were not statistically significant, because the test probability was higher than 0.05. Oxygen conditions in the Bobrza River worsened, a decrease in the values of oxygen indices values (DO, OSD) were registered below the sewage treatment plant. On the other hand, values of biochemical and chemical oxygen demand (BOD_5 and COD-Mn) and concentration of phosphate phosphorus ($P\text{-}PO_4$) was similar in both groups (Tab. 2).

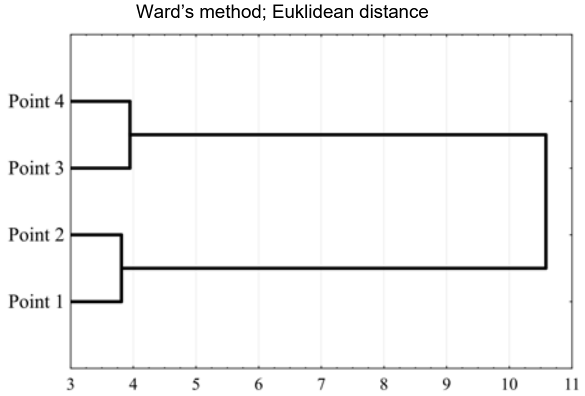

Fig. 2. Cluster analysis (dendrogram) similarity of physical and chemical indicators of water measurement and control; source: own study

Table 2. Comparison of the physicochemical indices values between the points above and below the treated sewage discharge using non-parametric U Mann–Whitney test

Indicator	Measurement-control point		Results of Mann–Whitney U test	
	above discharge	below discharge	test value *U*	probability test *(p)*
	median			
Temperature, °C	12.3	13.2	112	0.57
TSS, $mg \cdot dm^{-3}$	3.2	5.0	112.5	0.56
DO, mg $O_2 \cdot dm^{-3}$	8.5	7.4	101	0.32
OSD, %	91	87	111	0.53
BOD_5, mg $O_2 \cdot dm^{-3}$	2.1	1.9	114	0.61
COD-Mn, mg $O_2 \cdot dm^{-3}$	9.4	9.3	125.5	0.94
EC, $\mu S \cdot cm^{-1}$	372	520	51	0.004
TDS, $mg \cdot dm^{-3}$	211	292	36	<0.001
SO_4^{2-}, $mg \cdot dm^{-3}$	35.5	52.0	84.5	0.10
Cl^-, $mg \cdot dm^{-3}$	40.0	57.5	89	0.15
Ca^{2+}, $mg \cdot dm^{-3}$	47.0	55.0	59.5	0.011
Mg^{2+}, $mg \cdot dm^{-3}$	9.4	10.6	58	0.008
Na^+, $mg \cdot dm^{-3}$	21	39	50.5	0.003
K^+, $mg \cdot dm^{-3}$	4.6	9.6	50	0.003
$P\text{-}PO_4^{3-}$, $mg \cdot dm^{-3}$	0.044	0.046	118	0.72
$N\text{-}NH_4^+$, $mg \cdot dm^{-3}$	0.115	0.215	86.5	0.12
$N\text{-}NO_2^-$, $mg \cdot dm^{-3}$	0.04	0.06	107	0.43
$N\text{-}NO_3^-$, $mg \cdot dm^{-3}$	2.3	2.8	91	0.17
Fe, $mg \cdot dm^{-3}$	0.72	0.32	80	0.07
Mn^{2+}, $mg \cdot dm^{-3}$	0.18	0.14	103.5	0.36

Explanations: the highlighted statistical value are statistically important on the level $\alpha = 0.05$; other explanations as at the Tab. 1.
Source: own study.

Following its modernization in 2014, the sewage treatment plant improved its efficiency of nutrient (biogenic compound) removal, but not enough to allow the values of nitrite and nitrate nitrogen meet the requirements for surface water quality class I. According to NEVEROVA-DZIOPAK and CIERLIKOWSKA [2014], these compounds do not affect the intensity of the Bobrza River eutrophication. Similarly, while conducting research on the effect of mechanical and biological sewage treatment plant on water quality in the Zielawa and Lutnia watercourse, KRÓLAK *et al.* [2011] demonstrated that sewage treatment plants only slightly influence the increase in nitrate and ammonium ion concentrations and the electrolytic conductivity. They also determined that treated sewage discharged from the treatment plant in Wisznica and Piszczac did not have any direct effect on the receiving waters class. On the other hand LEWANDOWSKA-ROBAK *et al.* [2011], while assessing the effect of mechanical and biological sewage treatment with increased biogen removal on the Kicz stream water quality in Tuchola, the largest city of Bory Tucholskie, determined that in result of treated sewage discharge, concentrations of chlorides, nitrates (III) and

(V) and BOD_5 increased significantly in the receiving waters. However, it did not influence any change of water quality below the sewage discharge. KANOWNIK and RAJDA [2008] revealed in their hydrochemical research, that the Sudół Dominikański stream waters are continuously polluted by sewage discharge from the treatment plant in Węgrzce district. The load of supplied sewage proved too big in relation to water flow in the stream, which led to worsening of water quality in the watercourse. Also, research conducted by KOWALIK *et al*. [2015] on the Breń River revealed a considerable influence of treated sewage discharge from modernized mechanical and biological sewage treatment plant on the quality of receiving waters. The discharge caused increase in values of 12 out of 17 analysed physicochemical indices in the Breń River, of which in 8 cases these dependencies were statistically significant. It was found that BOD_5 values and the concentration of ammonium nitrogen affected the change of status from very good to good whereas in case of phosphates from very good to below good. Similar results were obtained for the Sudół stream near Kraków, where the discharge of treated sewage caused the increase in concentrations of most analysed quality indices in the stream water. Below the discharge from the treatment plant, over 100-fold increase in ammonium nitrogen was noted in the Sudół stream water, 10-fold increase in BOD_5 values and phosphate concentrations and over 5-fold increase in the concentrations of total suspended solids and nitrite nitrogen. These were the reasons for water quality worsening and its classification to the status below good [KANOWNIK *et al.* 2016]. The problem of changes of receiving waters quality caused by treated sewage discharge to the surface waters concern many regions of the world. Results of tests on water originating from Mamasin reservoir in Turkey evidence increased concentrations of nitrates and ammonium nitrogen due to discharging industrial and domestic sewage [SCANES 2011]. Studies on the effect of treated sewage on water quality in the Blue River flowing on the border of Johnson Country and Kansas were conducted in Missouri State, US from 2003 to 2009. The environmental conditions were determined through an analysis of accumulated data and comparison of the concentrations of water quality indices above and below the collector outlet. Again, it was observed that modernization of the treatment plant improved the quality of treated sewage supplied to the Blue River, but still sewage discharge had a negative influence on the water quality and contributed to the increase in primary production [GRAHAM *et al.* 2010]. The issue of the assessment of treated sewage effect on forecasting ecological hazards was among others addressed in Slovenia, analyses were conducted on the Krka River water, to which treated municipal and industrial sewage is discharged from the city treatment plants. The sewage which was subjected to biological treatment contained high concentrations of organic nitrogen, ammonia, phosphates and zinc [COTMAN *et al.* 2004].

Factor analysis (FA) made possible reducing a set of 20 water quality indices, formerly used for their characterization to four mutually orthogonal factors,

Table 3. Loadings of 20 indicators parameters on significant VFs for groups the points above and below the treated sewage discharge

Indicator	Above discharge				Below discharge			
	VF1	VF2	VF3	VF4	VF1	VF2	VF3	VF4
Temperature, °C	0.195	0.315	0.912	–0.143	–0.399	0.028	0.899	–0.084
TSS, mg·dm^{-3}	0.691	–0.601	–0.016	–0.178	–0.803	0.203	–0.194	–0.132
DO, mg O_2·dm^{-3}	0.815	–0.385	0.185	0.373	–0.156	0.977	0.094	0.080
OSD, %	0.685	–0.262	0.529	0.408	0.042	0.942	0.324	–0.003
BOD_5, mg O_2·dm^{-3}	–	–	–	–	0.014	–0.820	0.047	0.520
COD-Mn, mg O_2·dm^{-3}	–0.906	–0.283	0.082	–0.017	0.224	–0.951	–0.132	–0.069
EC, μS·cm^{-1}	0.871	0.021	–0.450	–0.035	0.573	0.183	–0.226	0.725
TDS, mg·dm^{-3}	0.951	–0.020	0.007	–0.303	0.392	0.548	0.208	0.675
SO_4^{2-}, mg·dm^{-3}	–0.230	0.771	0.176	0.206	0.808	–0.354	0.408	0.015
Cl^-, mg·dm^{-3}	0.159	0.454	–0.099	0.865	0.988	–0.017	0.116	0.006
Ca^{2+}, mg·dm^{-3}	–0.465	0.484	–0.515	0.507	0.969	–0.014	–0.072	0.223
Mg^{2+}, mg·dm^{-3}	–	–	–	–	0.884	–0.156	0.126	0.398
Na^+, mg·dm^{-3}	0.722	0.613	0.126	0.206	0.942	–0.035	–0.005	0.312
K^+, mg·dm^{-3}	–0.014	0.982	–0.060	0.111	0.904	–0.361	–0.088	0.160
P-PO_4^{3-}, mg·dm^{-3}	0.899	0.166	0.345	0.143	–0.256	0.207	0.113	–0.921
N-NH_4^+, mg·dm^{-3}	0.909	–0.045	–0.174	0.117	0.714	0.501	–0.386	0.190
N-NO_2^-, mg·dm^{-3}	0.052	0.944	0.082	–0.068	0.531	–0.718	–0.410	0.002
N-NO_3^-, mg·dm^{-3}	0.149	0.945	0.097	0.244	0.664	0.332	0.548	0.371
Fe, mg·dm^{-3}	0.010	0.019	0.994	0.020	0.252	0.330	0.880	–0.091
Mn^{2+}, mg·dm^{-3}	–0.256	–0.026	0.964	–0.006	0.317	0.294	0.877	–0.001
Eigenvalue	6.674	4.949	3.763	1.653	7.879	5.192	3.457	2.648
Total variance, %	37.1	27.5	20.9	9.2	39.4	26.0	17.3	13.2
Cumulative variance, %	37.1	64.6	85.5	94.7	39.4	65.4	82.7	95.9

Explanations: highlighted values indicate strong loadings.
Source: own study.

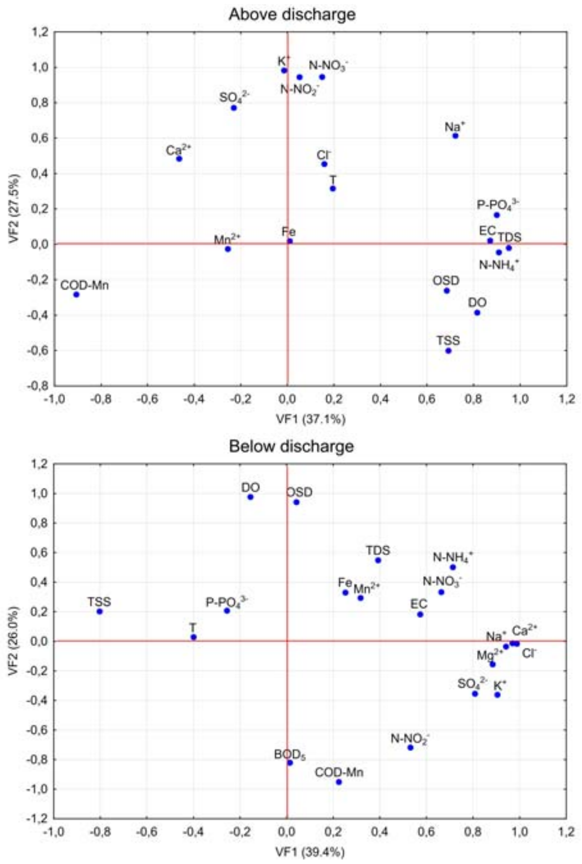

Fig. 3. Scatter plot of factor loadings of water quality parameters (above and below discharge of sewage) in the first and second factors; source: own study

like SOJKA *et al.* [2008]. The exposed factors have their own values higher than one and explain 95 and 96% of the internal structure of primary data, respectively for water above and below the sewage treatment plant (Tab. 3). It was assumed in the paper that when the factor loadings have values from 0.70 to 1.00, there is a strong dependence between the researched water quality indices and exposed factors. In case of waters above the treatment plant, the first factor explains about 37% of the primary dataset variability and is positively correlated with concentrations of dissolved oxygen, *EC*, dissolved solids, sodium, phosphate phosphorus and ammonium nitrogen, while negatively correlated with COD-Mn (Fig. 3), which is connected with pollutants originating from the built-up and urbanized areas [RAJDA, KANOWNIK 2006]. Concentrations of phosphates, potassium, nitrite nitrogen and nitrate nitrogen were positively correlated with the second factor, explaining about 28% of the primary data variability. It is associated with surface runoffs from the agricultural areas [KOWALIK *et al.* 2014]. The temperature and concentrations of iron and manganese were positively correlated with the third factor explaining about 21% of the primary data variability. The occurrence of these indices in rivers is connected with seasonality of rock and soil leaching in the catchment and the river channel, these pollutants are of natural origin [KANOWNIK *et al.* 2013]. Water in the Bobrza River below the sewage treatment plant was characterized by a slightly different dynamics. Concentrations of phosphates, chlorides, calcium, magnesium, potassium and ammonium nitrogen were positively correlated with the first factor explaining 39% of the data internal structure, whereas total suspended solid concentration was correlated negatively (Tab. 3). The factor is treated sewage discharge to the Bobrza River. Dissolved oxygen content in water (DO) and oxygen saturation degree (OSD), were positively correlated with the second factor, whereas concentrations of nitrite nitrogen, BOD_5 and COD-Mn values were correlated negatively. The third factor explaining about 17% of the primary data variability was positively correlated with the temperature and concentrations of iron and manganese. It is the same factor, which for the points above the sewage discharge was connected with the catchment geological structure.

CONCLUSIONS

The following conclusions were formulated on the basis of presented research results.

1. The Bobrza River waters along the studied stretch were classified to the potential below good due to exceeded limit values for class II for chemical oxygen demand (COD-Mn) and concentrations of chlorides (Cl^-), calcium (Ca^{2+}) and nitrite nitrogen ($N\text{-}NO_2$). Moreover, exceeded limit values for class II for biological oxygen demand (BOD_5) was stated in the Bobrza River water above the treatment plant, whereas below the treatment plant for electrolytic conductivity (*EC*).

2. Cluster analysis allowed to identify 2 groups of measurement-control points (above and below the sewage discharge point from the Sitkówka treatment plant) with similar values of water quality indices.

3. Discharge of treated sewage caused a worsening of 18 out of 20 studied indices in the Bobrza River water, including statistically significantly higher values of electrolytic conductivity, total suspended solids, calcium, magnesium, sodium and potassium noted in the Bobrza River water below the discharge. A decrease in dissolved oxygen content in the water and increase in its electrolytic conductivity caused a change of water quality class in the Bobrza River from the maximum potential to potential below good.

4. Factor analysis conducted on a set of 20 water quality indices below sewage discharge identified four orthogonal factors, which affect pollutant occurrence in the Bobrza River water. The first factor evidences the presence of compounds originating from the sewage discharge, the second is connected with worsening oxygen conditions in the water, the third results from seasonality and is responsible for the pollutants originating from natural sources, whereas the fourth factor has not been identified yet.

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Wpływ oczyszczalni ścieków Sitkówka na jakość wody rzeki Bobrzy

STRESZCZENIE

W pracy przedstawiono analizę 20 elementów fizykochemicznych w wodzie rzeki Bobrzy pobranej powyżej i poniżej miejsca zrzutu oczyszczonych ścieków. Mechaniczno-biologiczna oczyszczalnia Sitkówka zaprojektowana na 289 000 równoważnej liczby mieszkańców (RLM) odprowadza średnio na dobę 51 000 m^3 oczyszczonych ścieków, co stanowi aż 29% średniego natężenia przepływu wody w Bobrzy. Na podstawie hydrochemicznych badań stwierdzono, że zrzut oczyszczonych ścieków spowodował pogorszenie 18 z 20 badanych wskaźników jakości wody rzeki Bobrzy. W wodzie z rzeki poniżej zrzutu ścieków odnotowano statystycznie istotnie większe wartości przewodności elektrolitycznej właściwej, substancji rozpuszczonych, wapnia, magnezu, sodu oraz potasu. Zmniejszenie zawartości tlenu rozpuszczonego w wodzie i zwiększenie jej przewodności elektrolitycznej właściwej spowodowało zmianę klasy jakości wody w rzece z potencjału maksymalnego do potencjału poniżej dobrego. Natomiast zwiększenie stężenia substancji rozpuszczonych i siarczanów spowodowało zmianę klasy wody z potencjału maksymalnego do dobrego. Statystyczna analiza czynnikowa (FA) umożliwiła zredukowanie zbioru 20 elementów fizykochemicznych do czterech czynników wzajemnie ortogonalnych objaśniających 95% (powyżej oczyszczalni ścieków) i 96% (poniżej oczyszczalni ścieków) wewnętrznej struktury danych pierwotnych. Pierwszy czynnik jest związany z zanieczyszczeniami punktowymi (zrzutem ścieków), drugi opisuje warunki tlenowe w wodzie, trzeci wynika z sezonowości i odpowiada za zanieczyszczenia pochodzące ze źródeł naturalnych, natomiast czwarty czynnik nie został jednoznacznie zidentyfikowany.

Słowa kluczowe: *jakość wody, monitoring środowiska, zanieczyszczenia, zrzut ścieków*