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Changes in Selected Water Quality Indicators of the Warta River Due to the Jeziorsko Dam Reservoir

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1. Introduction

Assessing and interpreting of data on the quality of water in reservoirs and their impact on the quality of river water flowing through such reservoirs is a complex problem due to numerous factors and determinants. Regrettably, existing literature on the subject offers many examples limited to very simplistic approaches (Pytka et al. 2013, Pęczuła & Suchora 2011).

Reservoirs, according to flow characteristic, have features more or less similar to a very dynamic lakes (Wetzel 1990). Physical, chemical and biological characteristics allows to distingue three regions (zones): initial zone, transition zone and lentic region (Soares et al. 2008). Similar reservoir division into the zones described Straskraba (1999), noticing that even the whole reservoir can be treated as river-like or lake zone, depending on the water retention time and that the retention time influences both the longitudinal and the vertical patterns. Accordingly to these zones identification, it is valuable to note, that the first zone can occur as separate reservoir, named pre-dam, which can contribute to over 50% of nitrogen and phosphorus elimination (Czamara et al. 2008).

Damming rivers involves several important features and conditions, e.g. related to reservoir volume – water temperature and thermal stratification, residence time, turbidity, primary production and related to the construction – oxygen and nutrient balance or organic carbon cycle (Teodoru & Wehrli 2005, Friedl & Wüest 2002) and related also to watershed and catchment features (Soares et al. 2008).

There are contradict results of studies related to reservoirs impact on the matter and pollutants being transported by the river, e.g. Czamara et al. (2008) reported that large reservoirs can temporarily sink 90% of the total load of inflowing matter and biogenic substances, what corresponds to other authors remarks (Liu et al. 2019, Teodoru and Wehrli 2005). However Teodoru and Wehrli (2005) indicated a slight increase in nutrient loads before the dam (18% of total nitrogen and 13% of total phosphorus) and reported only 1% of nutrient retention in the Iron Gate Reservoir.

Liu et al. (2019) indicated basic processes of removal nutrients in reservoirs: temporary storage in biomass, denitrification and burial of sediment. Recirculation of elements and substances from the sludge to the water depth depends on: sediment bioturbation (Parsons et al. 2017) water body morphology (average depth) (Waters & Curran 2015), meteorological conditions, advection, speed and thermal stratification, dissolved oxygen concentration and red-ox potential (Lee et al. 2019).

Nitrogen compounds can be realized or absorbed at different time scales and its daily retention is influenced by flow velocity and water level (Liu et al. 2019).

There are a few processes and phenomena related to the amount of phosphorus in water, e.g. dependency on the external and internal load from the sediments. The amount of phosphorus released in the sediment depends on the duration and surface extent of anoxia and the rate at which phosphorus is released from the anaerobic surface of the sediment (Lee et al. 2019).

A reliable assessment of changes in the quality of water along the watercourse, taking into account the reservoirs through which it flows, requires a balance of inflow and outflow loads, data on real retention times and flow rate velocities as well as identification of potential and ongoing processes (Pawełek & Grenda 2010, Wiatkowski 2011). If the (transformation) time of a particular substance or related demand for it (identified by a specific pollution indicator) does not change significantly, the existing relationship is simpler to interpret.

The process of self-cleaning is a fundamental issue related to water quality in watercourses and yet, a very complex one, with intensity depending on numerous factors. The observed as well as future increase in water temperature will modify current processes occurring in the river, referring to among others water quality, composition of ichthyofauna, or hydrological conditions. A fairly common approach to this process (Starmach et al. 1976) includes, among others: the section length where the process is analysed, the self-cleaning rate per unit of time, the biologically active surface and the activity of organisms present in a given ecosystem. There are also known approaches based on the use of specific self-cleaning factors (indicators). The most commonly considered indicators in the context of water self-cleaning capacity are dissolved oxygen in water (DO) and biochemical oxygen demand over five days (BOD_5). Depending on the conditions, other indicators – nitrogen and phosphorus – are also included (Jaskuła et al. 2019). A decrease in the concentration of ammonium ions is considered a fairly representative indicator of water self-cleaning capacity, which proves good oxygenation of water as well as a proper run of nitrification and biological assimilation processes.

One of the important hydrological parameters to be analysed in this context is the actual water retention time in the reservoir, which, in turn, is crucial for possible processes requiring a specific time. As a result, time intervals for determining these indicators should be adapted to the duration of specific processes and the actual water retention time in the reservoir (Soares et al. 2008).

Despite a fairly wide scope of standard analyses performed for surface waters, their usefulness often raises significant doubts, except for identifying variations and trends of changes over time, meeting or failing some formal criteria and evaluating the process of eutrophication. Therefore, it seems reasonable to ask whether the data provide information on other important processes.

Numerous works and studies to date, even if they show differences between water quality at the inflow and outflow from the reservoir, supported with statistical analysis, (Wiatkowski 2010, Kanclerz et al. 2014, Bogdał et al. 2015), very rarely (Przybyła et al. 2014) give reasons for this state of affairs or identify processes leading to it.

The objective of the study was to evaluate, on the example of the Jeziorsko reservoir, the applicability of standard physical and chemical analyses of water (performed by the Institute of Environmental Protection and Water Management) in order to assess changes in selected water quality indicators of the Warta River under the impact of the Jeziorsko dam reservoir.

2. Methodology

The undertaken analyses concern the impact of the Jeziorsko reservoir on the quality of water in the Warta river. The reservoir was created as a result of partitioning the valley with a front dam. It is located on the border of the Wielkopolskie and Łódź voivodships in the middle course of the Warta River. Its usable capacity is 113.91 million m^3, and the total capacity equals 202 million m^3.

Since there is no hydrological data for smaller watercourses forming the catchment of the Jeziorsko reservoir (Fig. 1), the authors, in order to compare the amount of water flowing into the reservoir from the Warta river and the amount of water supplied from other inflows, compared the catchment surfaces. Based on Atlas Podziału Hydrograficznego Polski (the Atlas of the Hydrographic Division of Poland) (Czarnecka 2005), the Jeziorsko catchment area is 625.6 km^2, and the Warta catchment area is 9012.64 km^2. Direct inflows to the reservoir constitute 6.94% of the total area of the Warta river area at the front dam cross-section.

In view of their low share, apart from the Warta river, they were omitted as part of the analysis, assuming their impact as negligible or insignificant.

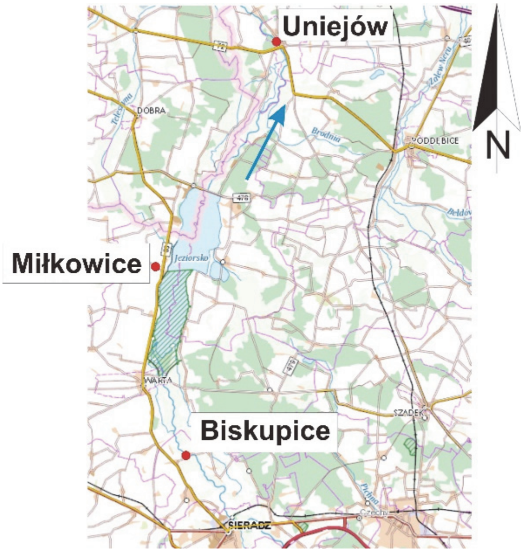

Fig. 1. Location of water sampling points

Water quality tests were carried out by the Voivodeship Inspectorate for Environmental Protection in Łódź, the Sieradz Inspectorate in the selected points: above in Biskupice, Miłkowice, below the Jeziorsko reservoir in Uniejów, no more than once a month and at least six times a year. The samples were taken in 2006, 2008, 2011, 2014. The following parameters belonging to the physical-chemical elements (supporting biological elements – thermal conditions, oxygenation conditions, organic pollutants, acidification state and biogenic conditions): temperature, pH, biochemical oxygen demand over five days (BOD_5), total phosphorus (P_{tot}), total organic carbon (TOC) and total nitrogen (N_{tot}) were used for analysing. All the analyses of water samples as well as assessments of water quality were carried out in accordance with applicable standards set out in the Regulation of the Minister of the Environment of July 21, 2016 on the classification of the state of surface water bodies and environmental quality standards for priority substances (Regulation Journal of Laws, item 1187 2016), Regulation of the Minister of Maritime Economy and Inland Navigation of 12 July 2019 on substances particularly harmful to the aquatic environment and the conditions to be met when discharging wastewater into waters or soil, as well as when discharging rainwater or meltwater into waters or into aquatic devices (Regulation Journal of Laws, item 1311 2019). For the purpose of this paper, as a representative of the impact of the reservoir on river water quality, there were arranged water sampling points near Biskupice (at 511.8 km of the Warta river) and below the dam in Uniejów (at 468.8 km of the Warta river). According to the JCWP, the Warta River is assigned to type 19, i.e. a sandy-clay lowland river. The R software was used for statistical computing. The statistical test was applied to assess the average differences in water quality indicators (pH, temperature, BOD_5, TOC, N_{tot}, P_{tot}) between the sampling point in Biskupice and the sampling point Uniejów through comparing the value of each indicator in individual months of the year. The Shapiro-Wilk test was used to examine normal distribution of samples in the first stage. In order to identify significant differences in water quality between the sampling point located in Biskupice and the sampling point Uniejów, the paired t-test was used for samples with normal distribution, and the Wilcoxon test for tied pairs – for distribution other than normal, at a substantial level of significance $p < 0.05$.

3. Results and discussion

A classic approach to qualitative analyses of reservoir waters requires a balance of direct inflows (from direct and indirect catchment areas) and outflows of pollution loads, particularly of biogenic nature (eutrophic – Galicka et al. 2007, Kanclerz 2011). However, for indicators with a statistically significant difference found between the sampling points, there was no data on loads introduced to the reservoir from the direct catchment: from point, spatial and scattered sources. Due to the fact that statistically significant differences occurred mainly for 2014 data, it seems that they had no decisive impact. In the analyses examining biogens, these sources accounted for up to 10% of the loads flowing into the Jeziorsko reservoir (Galicka et al. 2007).

The value of BOD_5 in the months in 2006 in Biskupice was on average 1.7 mg $O_2 \cdot dm^{-3}$, and Uniejów -2.2 mg $O_2 \cdot dm^{-3}$. In 2014, the average value was 2.15 mg $O_2 \cdot dm^{-3}$ in Biskupice and 2.81 mg $O_2 \cdot dm^{-3}$ in Uniejów (Fig. 2). The values of BOD_5 in Miłkowice in 2008 were between 1.26 and 5.26 mg $O_2 \cdot dm^{-3}$.

The results of statistical analysis showed that the average differences in BOD_5 between the sampling point in Biskupice and the sampling point located below the main dam (Uniejów) in 2006, 2011 and 2014 were -0.50, -0.32 and -0.66 mg $O_2 \cdot dm^{-3}$, respectively. The analysis of data indicated that BOD_5 samples taken in Biskupice and Uniejów in 2006 and 2011 showed normal distribution (the Wilcoxon test, $p > 0,05$). The results of the t-par test showed that there was no statistically significant difference at the level of significance $p < 0.05$ in 2006 and 2011, while in 2014 a statistically significant difference was observed between the samples taken in Biskupice and Uniejów.

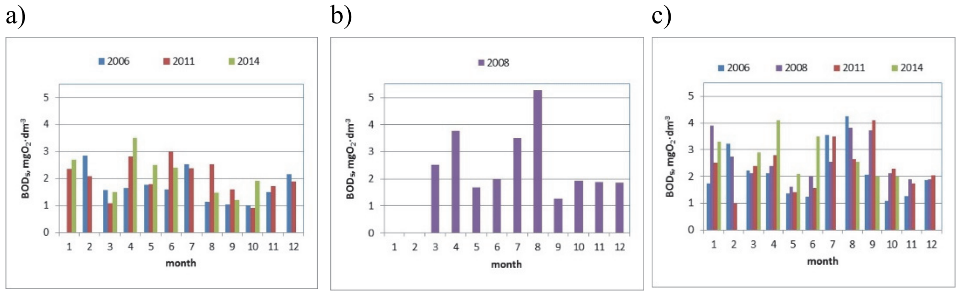

Fig. 2. Changes in the value of BOD_5 a) in Biskupice, b) in Miłkowice c) in Uniejów (below the main dam)

The results presented in Fig. 3 showed that in Biskupice the values of the analysed indicator were higher than in Uniejów. The values of pH in Miłkowice in 2008 were between 7.8 and 8.7.

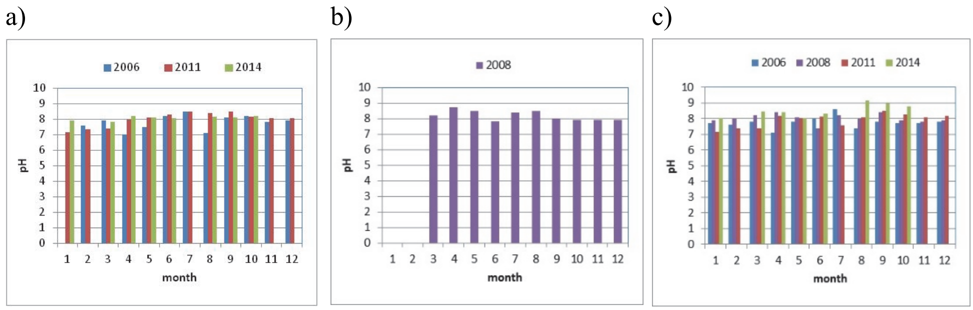

Fig. 3. Changes in the value of pH a) in Biskupice, b) in Miłkowice c) in Uniejów

Comparing the values of average water temperatures in 2006, 2011 and 2014, it was found that differences in temperature between the sampling points were -0.4°C, -0.5°C and 1.2°C, respectively.

When analysing Fig. 4, it can be stated that in most months the temperature was higher below the main dam than at the sampling point in Biskupice. The statistical analyses performed showed that the difference in temperature was not statistically significant in 2006 and 2011, and the paired t-test demonstrated that the difference in temperature in 2014 was statistically significant at the level of significance $p < 0.05$.

The average value of TOC in Biskupice in 2006, 2011 and 2014 was 5.68 $mg \cdot dm^{-3}$, 7.29 $mg \cdot dm^{-3}$ and 6.91 $mg \cdot dm^{-3}$, respectively, and at the sampling point Uniejów -6.26 $mg \cdot dm^{-3}$, 8.53 $mg \cdot dm^{-3}$ and 7.27 $mg \cdot dm^{-3}$ (Fig. 5). The statistical analysis for 2006 was carried out using the Wilcoxon test for samples with abnormal distribution. Average differences between the sampling points located above and below the main dam were in 2006, 2011 and 2014 -0.58 mg·dm^{-3}, -1.25 mg·dm^{-3} and -0.35 mg·dm^{-3}, respectively. This indicates that the values of TOC were higher in Uniejów than in Biskupice. Based on statistical computing, no significant difference was found between the values of sampling points at the level of significance $p < 0.05$. The values of TOC in Miłkowice in 2008 were highly differentiated – between 3.4 and 20.6 mg·dm^{-3}.

a) b)

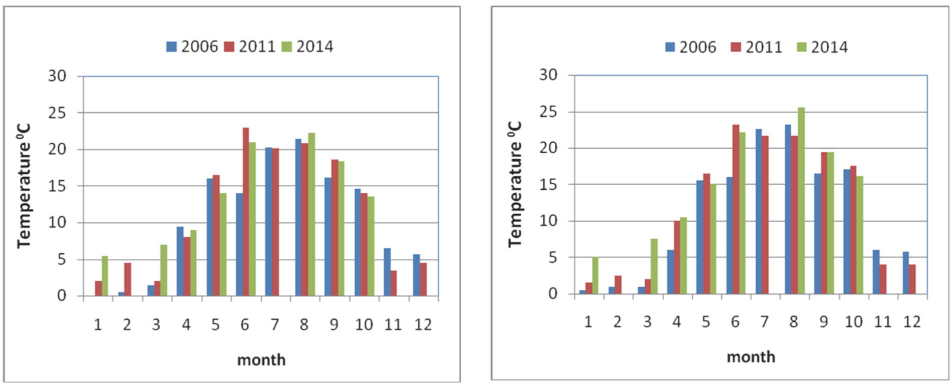

Fig. 4. Changes in the value of water temperature a) in Biskupice, b) in Uniejów

a) b) c)

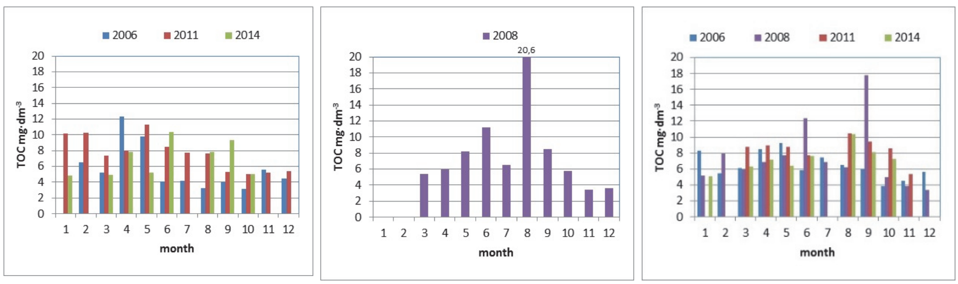

Fig. 5. Changes in the value of TOC a) in Biskupice, b) in Miłkowice, c) in Uniejów

Differences in average values between total phosphorus concentrations in 2006, 2011 and 2014 were -0.017 mg·dm^{-3}, 0.015 mg·dm^{-3} and 0.03 mg·dm^{-3}, respectively (Fig. 6). The difference in average values for total phosphorus between the sampling point in Biskupice and the sampling point located in Uniejów was not statistically significant at the level of significance $p < 0.05$ in individual years of the study. The values of P_{tot} in Miłkowice in 2008 were between 0.05 and 0.19 mg·dm^{-3}.

The results of statistical analysis for total nitrogen in 2006, 2011 and 2014 showed that differences in average values between the sampling point in Biskupice and the sampling point located in Uniejów were 2.97, 0.27 and 0.8 mg·dm^{-3}, respectively (Fig. 7). The values of N_{tot} in Miłkowice in 2008 were higly changeable – between 0.85 and 4.48 mg·dm^{-3}.

a) b) c)

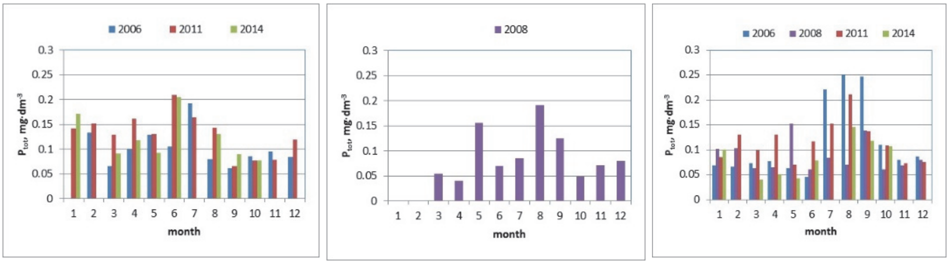

Fig. 6. Changes in the value of P_{tot} a) in Biskupice, b) in Miłkowice, c) in Uniejów

a) b) c)

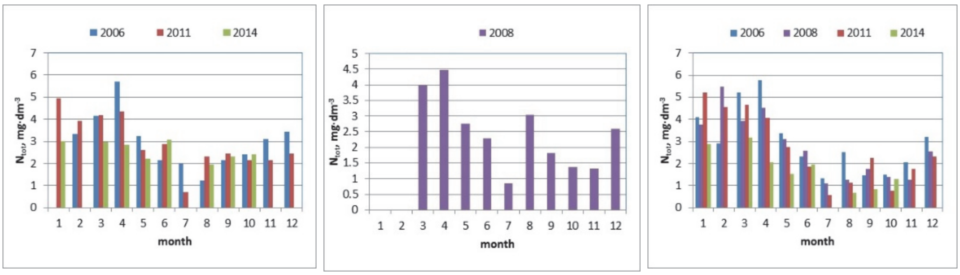

Fig. 7. Changes in the value of N_{tot} a) in Biskupice, b) in Miłkowice, c) in Uniejów

The results of statistical analysis showed that there was no statistically significant difference in the average index of total nitrogen between the sampling point in Biskupice and the sampling point below the main dam (Uniejów) in 2011 ($p > 0.05$).

The average content of N_{tot} in 2006, 2008, 2011 and 2014 in samples taken from the sampling point in Uniejów was 2.88 mg·dm^{-3}, 2.35 mg·dm^{-3}, 2.66 mg·dm^{-3} and 1.80 mg·dm^{-3}, respectively, and in samples taken in Biskupice in those years -3.00 mg·dm^{-3}, 2.45 mg·dm^{-3}, 2.93 mg·dm^{-3}, respectively.

The result of average differences in the analysis of water quality in 2006, 2011 and 2014 between the sampling point in Biskupice and the sampling point located in Uniejów showed that the concentration of N_{tot} in all years was higher in Biskupice than at the point located in Uniejów. The decrease between Biskupice and Uniejów could result from nitrogen utilisation by live biomass in the reservoir. The values of following indicators: temperature, BOD_5, TOC in all analysed years were higher in Uniejów than in Biskupicewas higher in Biskupice and lower in Uniejów, while in 2014 it was the opposite. The variability analysis of P_{tot} indicator showed that in 2006 it was higher below the dam, and in 2011 and 2014 it took higher values at the sampling point located in Biskupice. The differentiated P_{tot} concentrations at Biskupice and Uniejów sampling taken points and its opposite trends (comparing 2006 and 2011/2014 years) was the result of phosphorus compounds release or absorption by bottom sediments at changeable oxic/anoxic conditions (Lee et al. 2019).

For most indicators, slightly higher average values were found below the dam (Uniejów) compared to the sampling point above the dam in Biskupice. In the analysed years, the average N_{tot} index was higher above the dam. In most cases the difference was very small.

Among a few indicators analyzed for Miłkowice and Uniejów sample taken point only TSS and N_{tot} showed some decrease (TSS) or increase (N_{tot}). Very little decrease was observed in case of TOC. Although none of these differences was statistically significant (95% confidence interval for matched pairs data).

Table 1. The average value of differences and statistical significance of the analysed water quality indicators between Biskupice and Uniejów in 2006, 2011, 2014, Miłkowice and Uniejów in 2008

Indicator	2006		2008		2011		2014	
	Average differences	p	Average differences	p	Average differences	p	Average differences	p
Temperatura (°C)	-0.40	0.46	–	–	-0.53	0.20*	-1.29	0.02
BOD_5 (mg $O_2 \cdot dm^{-3}$)	-0.50	0.13	-0.15	0.47	-0.32	0.33	-0.66	0.02
TOC ($mg \cdot dm^{-3}$)	-0.58	0.32*	-0.32	0.56	-1.25	0.16	-0.39	0.57
N_{tot} ($mg \cdot dm^{-3}$)	2.97	<0.01	-0.10	0.62	0.27	0.17	0.80	0.01
P_{tot} ($mg \cdot dm^{-3}$)	-0.02	0.89*	-0.01	0.81	0.02	0.30	0.04	0.11

* Wilcoxon test for tied pairs – for distribution other than normal

(-)values below the dam (Uniejów) higher than for the point in Biskupice

The analysis of these determinations has shown that they are sufficient for assessing the status of water, also in terms of its eutrophication, however, they do not provide too many opportunities to analyse processes, phenomena, trends and variations, particularly their causes.

Additionally, the quality of water flowing out of the reservoir is affected by the frequency and time of discharges and their method from hydroelectric power plant or overflow.

In 2006, the largest water inflows to the reservoir occurred in the second half of February and from the third decade of March to mid-May. In contrast, water outflows larger than the designed water flow rate of the power plant were observed from early April to mid-May, counting for 51 days. The average daily water retention time in the reservoir in 2006 was 26 days (minimum 8 and maximum 85 days). The longest average daily retention time was recorded from the beginning of June to the end of the first decade of September.

The largest water inflows and outflows from the Jeziorsko reservoir in 2011 occurred from the beginning of January to the beginning of April. Water outflows larger than the designed water flow rate of the power plant lasted for 63 days from the beginning of the year. The average annual inflow and outflow of water from the reservoir were 55.5 $m^3 \cdot s^{-1}$ and 58 $m^3 \cdot s^{-1}$, respectively. In 2011, the average daily water retention time in the reservoir was 28 days. Retention times ranged from 8 to 65 days, and the longest times were observed from the end of March to mid-July and from mid-August to the end of the first decade of September.

Water inflows to the Jeziorsko reservoir in 2014 were more compensated than in 2006 and 2011, because the maximum values in these years were 212 $m^3 \cdot s^{-1}$ and 226 $m^3 \cdot s^{-1}$, respectively, while in 2014 it was only 70 $m^3 \cdot s^{-1}$. Water outflows larger than the designed water flow rate of turbines lasted a total of 16 days. These outflows occurred in May (7 days) and December (7 days), and the remaining two days – in other months of this analysed year. The average annual inflow and outflow of water was 40 $m^3 \cdot s^{-1}$. During 2014, the average daily water retention time in the Jeziorsko reservoir was 32 days (minimum 7 and maximum 73 days). The longest retention times were recorded from mid-March to mid-May and from mid-June to mid-September.

The actual water retention time in reservoirs is sometimes much longer or shorter than the interval between sampling times, which can make interpretation of the results difficult (if the substance concentration has changed over time, then the dilution or concentration will increase due to the retention time). When the concentration of a substance in the inflow increases for a moment, and in the absence of its decomposition, there is a simple relationship of "delay" between the peak and the actual retention time. However, such situations, independent of other factors, are quite rare in practice. It is also important to remember, what has already been mentioned, that constant concentration does not necessarily mean that there is no change in a particular substance, since it can be the result of balancing its increase and decomposition rates.

Due to numerous factors and determinants, as well as the lack of data continuity, it is challenging and fallible to interpret the state of water quality in reservoirs in the context of their impact on the quality of watercourses (rivers). This difficulty is related to i.e. the actual water retention time in the reservoir (problematic to determine), lack of data on the periods between measurements (periods of occurrence of specific concentrations of pollutants and nutrients, associated with the introduced load). Yang et al. (2012) stated the degradation of water quality associated with excess levels of nitrogen and phosphorus impacted by interactions among agriculture and urban factors. For the interpretation of water quality, it is also important to know the local flow rates that have a decisive effect on the sedimentation rate of suspensions. In the context of suspensions, it is equally necessary to have a methodology to determine them, particularly the minimum particle size. Additionally, for suspensions, but also for compounds accumulated in sediments and debris, sediment thickness and flow velocity in their immediate vicinity may be of key importance.

4. Conclusions

Despite certain dependencies or trends in particular cases, few measurements and their high variability do not allow for drawing cause and effect conclusions. A larger number of measurements would definitely help demonstrate the statistical significance of differences. The analysed data, despite pointing to a certain "tendency" for the majority of pollution indicators (water quality) do not confirm these relationships due to significant variations in the values of indicators. Most indicators were characterised with the significance of differences for the study carried out in 2014. It is known that often in such situations more data is required to demonstrate statistical significance. Compilation of data in an appropriate range and a sufficient amount, at least in some cases, may allow for estimating the actual retention time in the reservoir without using data related to the work of individual elements of the water barrage. The following conclusions can be drawn based on this study:

1. The study did not show a statistically significant difference between the average differences in parameters between the sampling point in Biskupice and the sampling point below the dam in 2006 and 2011 (in the 95% confidence interval).

2. However, a statistically significant difference was found in the average values for most parameters measured in 2014, except for TOC and P_{tot} (in the 95% confidence interval).
3. Among a few indicators analyzed for Miłkowice and Uniejów sample taken point only TSS and N_{tot} showed some decrease or increase, however none of these differences was statistically significant.
4. Routine tests of surface water quality are difficult to analyse in terms of the impact of the dam reservoir on the quality of river waters.

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Rozporządzenie Ministra Środowiska z dnia 21 lipca 2016 r. w sprawie sposobu klasyfikacji stanu jednolitych części wód powierzchniowych oraz środowiskowych norm jakości dla substancji priorytetowych (Dz. U. poz. 1187)

Rozporządzenie Ministra Gospodarki Morskiej i Żeglugi Śródlądowej z dnia 12 lipca 2019 r. w sprawie substancji szczególnie szkodliwych dla środowiska wodnego oraz warunków, jakie należy spełnić przy wprowadzaniu do wód lub do ziemi ścieków, a także przy odprowadzaniu wód opadowych lub roztopowych do wód lub do urządzeń wodnych (Dz. U. poz. 1311)

Abstract

Many factors affect the quality of water in rivers, including: types of pollution sources, the shape of the catchment, the type of land use, the amount of pollution flowing in. The construction of a retention reservoir is one of the factors affecting changes in the river valley related to the landscape, the environment, and water flow hydraulics. Reducing the velocity of water flow on the section of the reservoir causes changes in the characteristics of the movement of pollutants, some of them are deposited in the reservoir. The article analyzes water quality parameters at intake points located below (Uniejów) and above (Biskupice) of the Jeziorsko dam on the Warta River. The variability of such parameters as BOD_5, TOC, pH, temperature, N_{tot}, P_{tot} was analyzed. The research also analyzed the dynamics of water inflow and outflow from the reservoir. The actual water retention time in the reservoir, which makes interpretation of the results difficult. The most indicators were characterized by the significance of differences for research in 2014.

Keywords:
water quality, reservoir, Warta river, pollutant, nutrient

Zmiany wybranych wskaźników jakości wody rzeki Warty pod wpływem zbiornika zaporowego Jeziorsko

Streszczenie

Na jakość wody w rzekach wpływa wiele czynników do których należą: rodzaje źródeł zanieczyszczeń, ukształtowanie zlewni, rodzaj użytkowania terenu, ilość dopływających zanieczyszczeń. Budowa zbiornika retencyjnego jest jednym z czynników wpływających na zmiany w dolinie rzecznej związane z krajobrazem, środowiskiem, hydrauliką przepływu wody. Zmniejszenie prędkości przepływu wody na odcinku zbiornika powoduje zmiany w charakterystyce przemieszczania się zanieczyszczeń, część z nich osadza się w zbiorniku. W artykule przeanalizowano parametry jakości wody w punktach poboru zlokalizowanych poniżej (Uniejów) i powyżej (Biskupice) zapory zbiornika Jeziorsko na rzece Warcie. Analizie poddano zmienność takich parametrów jak BZT_5, OWO, pH, temperatura, N_{og}, F_{og}. W badaniach przeanalizowano również dynamikę dopływu i odpływu wody ze zbiornika. Rzeczywisty czas retencji wody w zbiorniku jest różny co utrudnia interpretację wyników. Najwięcej wskaźników charakteryzowało się istotnością różnic dla badań w 2014 roku.

Słowa kluczowe:
jakość wody, zbiornik retencyjny, rzeka Warta, zanieczyszczenie, biogen