JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2023.143749
2023, No. 56 (I–III): 91–101

Influence of the manner of water discharge from dam reservoirs on downstream water quality

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RECEIVED 19.04.2022 ACCEPTED 24.06.2022 AVAILABLE ONLINE 13.03.2023

Abstract: The study was carried out in the area of three dam reservoirs: Blizne and Maziarnia (Voivodeship of Podkarpackie) and Nielisz (Voivodeship of Lublin). The main parameter differentiating the reservoirs was the water retention time and the manner of water discharge from the reservoirs. Three test sites were designated in the area of each reservoir: in the river zone of the reservoir, in the central part of the reservoir, and near the reservoir dam. At these sites, the concentrations of suspended sediment in the water and the content of organic matter in it, the concentrations of total phosphorus and total nitrogen, as well as chlorophyll *a* were monitored. In addition, two control sites were established: on the river upstream of the reservoir and on the river downstream of the dam, respectively. At these points, the concentrations of suspended sediments in the water and their organic matter content were recorded. The obtained results of the study and multivariate analysis of the data showed that morphometric parameters (including water retention time) of reservoirs and the method of water discharge influence water quality in downstream rivers. It was found that by using lower discharge and ensuring a sufficiently long retention time of water in the reservoir, it is possible to effectively limit the negative aspects of hydrotechnical structures' impact on the natural environment.

In practice, the observed relationships may constitute an important and missing link in the aspect of minimising undesirable side effects of this type of hydrotechnical objects.

Keywords: dam, environmental pollution, organic matter, retention reservoirs, suspended sediment, water quality, water resources

INTRODUCTION

Reservoirs are engineering-technical creations of human activity (pressure) in the natural environment. As a result of fording natural rivers by hydrotechnical construction (dam) a reservoir is created, often called also an artificial lake. Despite their seeming similarity, dam reservoirs are significantly different from natural lakes. These objects are separate aquatic ecosystems, consolidating different features of the environment proper to lakes and rivers. In the inflow zone of the reservoir, conditions typical of rivers dominate, while near the dam conditions are closer to lake ecosystems. A characteristic feature of dam reservoirs is generally short water retention time, large fluctuations in water capacity and water level and asymmetry in reservoir basin shape [Jankowski 2017; Ostrowska, Sałdak 2015; Traczewska 2012]. In addition, compared to river water properties, water stored in reservoirs heats up more slowly, but also cools down more slowly, i.e. it has the so-called thermal capacity (water temperature in the reservoir is usually higher than in the river below and upper the reservoir) [Jankowski 2017; Rzętała 2008]. The variation of the reservoir filling level along the longitudinal axis modifies, among other things, the oxygen and nutrient conditions and life cycles of organisms in the characteristic zones of the reservoir (river zone, transitional zone, lake zone). The lowest water level is found at the inflow, gradually increasing towards the dam, where the difference in water level can reach even several dozen metres. In deeper parts of the reservoir a distinct temperature differentiation (stratification) can occur between the surface and bottom zones of the reservoir [Chapman (ed.) 1996].

An important element determining the property of dam reservoirs is the intensity of water exchange or its retention time.

According to the classification proposed by STARMACH *et al.* [1978], limnic reservoirs are distinguished, where full water exchange occurs less than 10 times a year (retention time > 36 days) and reolimnic reservoirs, where water exchange occurs more than 10 times a year (retention time < 36 days). Limnic reservoirs are dominated by lake features, while reolimnic reservoirs are dominated by river features [BARTOSZEK, CZECH 2014; STARMACH *et al.* 1976]. One can also find an additional division into super-reolimnic reservoirs (watersheds), where total water exchange occurs more than 35 times per year (retention time < 10 days) [GIZIŃSKI 2003].

A specific feature of the functioning of dam reservoirs is the ongoing transport of suspended sediment from the catchment and its accumulation in bottom sediments, resulting in their shallowing and degradation. It is assumed that suspended sediment is a mixture of a dispersed phase (solid particles) and a distracting medium (water) that interacts with each other in a dispersive system. The dispersed phase includes both mineral and organic components [LEE *et al.* 2019; NOCOŃ 2012]. The organic phase of the complex consists of animate organisms (including bacteria, phytoplankton and zooplankton) and their inanimate forms (e.g., fecal and pseudo-fecal pellets, detritus and its decomposition products from microbial activity such as mucus and exopolymers) [LEE *et al.* 2019], as well as xenobiotic particles from human activities (e.g., microplastics) [ZIEMBOWICZ *et al.* 2018]. A complex containing organic carbon, dissolved organic nitrogen and dissolved organic phosphorus forms dissolved organic matter [PALVIAINEN *et al.* 2016]. Dissolved organic matter includes residual microorganisms at various levels of decomposition and readily decomposable non-humic organic matter. As it is the most mobile and easily decomposable organic fraction, it is an important part of energy and nutrient distribution for microorganisms [BOLAN *et al.* 2004; HAYNES 2000; POIRIER *et al.* 2005]. Organic matter content is also one of the most important indicators of environmental pollution. It represents the total load of all organic pollutants present in the studied ecosystem [PIETRZYK, PAPCIAK 2016].

The main objective of this study was to assess the impact of damming natural rivers with a hydrotechnical construction (dam) on water quality.

MATERIALS AND METHODS

STUDY AREA

Three dam reservoirs, differing in morphometric parameters, located in South-Eastern Poland, were selected for the study (Fig. 1). The reservoirs were Blizne (GPS 49°74'18.4" N, 22° 00'96.1" E) and Maziarnia (GPS 50°33'22.8" N, 21°94'01.8" E) (Voivodeship of Podkarpackie) and Nielisz (GPS 50°78'34.7" N; 23°01'71.2" E) (Voivodeship of Lublin). One of the basic parameters differentiating the selected reservoirs was the water retention time (Tab. 1) and the construction and technical parameters of the dam.

The Blizne Reservoir is located within the boundaries of the community (local authority area) Jasienica Rosielna (South-Eastern region of Poland). The commune occupies an area of about 58 km^2, of which 63% is agricultural land and 27% forest [MIĄSIK *et al.* 2014]. Agricultural production plays the main role in shaping the anthropogenic impact. The studied object is part of a cascading system of two reservoirs – lower and upper. The reservoirs were created by damming the Łądzierz Stream with a frontal earthen dam. The dam of the lower reservoir (where the study was conducted) is 140 m long, 4 m high and has a crown width of 3 m and is equipped with an (upper) overflow water discharge [CIEŚLA *et al.* 2019].

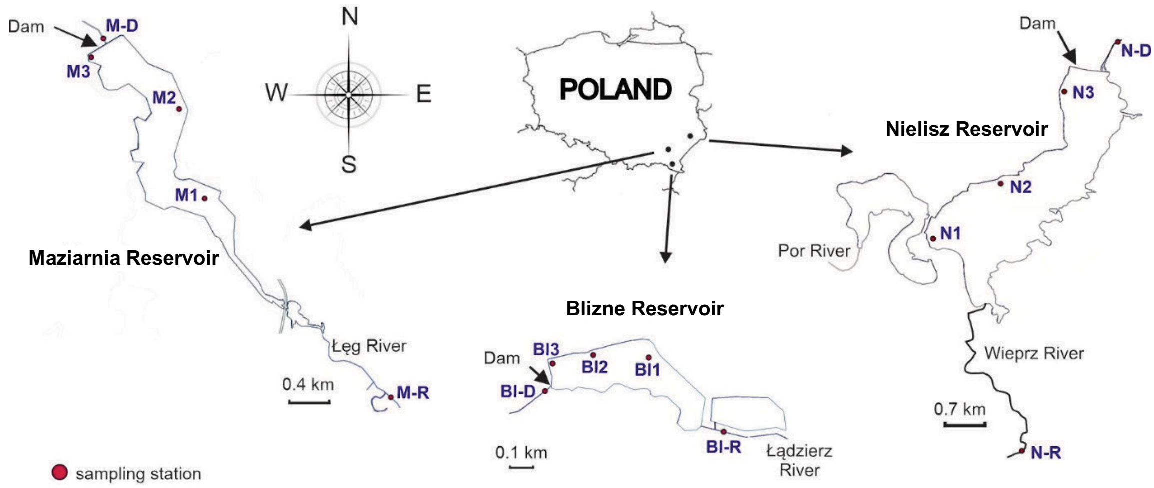

Fig. 1. Location of reservoirs and research sites; source: own elaboration

Table 1. Selected basic morphometric parameters of the studied reservoirs

Specification	Blizne	Maziarnia	Nielisz
Year of commissioning	2002	1989	2006
River/stream	Łądzierz	Łęg	Wieprz, Por
Reservoir area (ha)	8.66	102.0	914.0
Total capacity (mln m^3)	0.137	2.75	20.61
Maximum depth (m)	3.9	8.76	8.58
Biological flow (m^3·s^{-1})	0.022	0.117	3.0
Mean retention time (d)	18.0	36.0	77.0

Source: own elaboration.

The Maziarnia Reservoir is located in Wilcza Wola, on the territory of Podkarpackie Voivodeship, within the Dzikowiec community (the region of South-Eastern Poland). The area of the community occupies about 122 km^2, of which agricultural land constitutes 54% and forested land 39% [GRUCA-ROKOSZ 2018]. The analysed object is an artificial dam reservoir, built on the Łęg River. The frontal earthen dam of the reservoir with a ferro-concrete weir has a length of 420 m and a crown width of 6 m. In the body of the weir there are lower outlet with dimensions of 2.0 × 2.0 m [GAMRACY 2011].

In turn, the Nielisz Reservoir is located in the community of Nielisz and Sułów (Voivodeship of Lublin). On average 67% of the catchment area is agricultural land, of which the largest area is arable land, orchards, meadows and pastures. The main sources of pollution in the catchment are wastewater treatment plants, which collectively discharge about 2.8 mln m^3 of municipal wastewater and about 1.0 mln m^3 of industrial sewage (as of 2009) [JANCEWICZ *et al.* 2012]. The reservoir was constructed on the basis of an earth dam and ferro-concrete weir with a length of 845 m. Water can be discharged from the facility either through the upper overflow (maximum discharge of about 220 $m^3 \cdot s^{-1}$) or through the lower outlet. The lower outlet, with a maximum flow capacity of about 6.2 $m^3 \cdot s^{-1}$, supplies water to a set of hydroelectric turbines [NIEDABYLSKI, TCHÓRZ 2017].

RESEARCH METHODS

Research conception

The research was conducted during the spring and summer of 2018 and 2019. In 2018 (from 8th May 2018 to 11th September 2018), the research was conducted simultaneously on two reservoirs: Blizne and Maziarnia. While, in 2019 (from 8th May 2019 to 27th August 2019) the research was carried out on Nielisz Reservoir. Three study sites were designated within each reservoir: in the river zone of the reservoir (BL1, M1, N1), in the central part of the reservoir (BL2, M2, N2), and near the dam (BL3, M3, N3). Concentrations of suspended sediment (*SS*) and organic matter in them (OM_{SS}) as well as concentrations of total phosphorus (TP_W), total nitrogen (TN_W) and chlorophyll *a* (Chl*a*) were monitored at those sites.

In addition, two control sites were established on the river upstream of the reservoir (BL-R, M-R, N-R) and on the river downstream of the dam (BL-D, M-D, N-D), respectively. Concentrations of suspended sediment (*SS*) and organic matter content in them (OM_{SS}) were monitored at these sites. The detailed location of the sites is shown in Figure 1. Detailed information on the dates and number of measurements is presented in Supplementary materials (Tabs. S1–S9). Supplementary materials can be accessed in the 4TU. ResearchData repository (the DOI of dataset: https://doi.org/10.4121/20151527.v1).

Physico-chemical analysis of water samples

Suspended sediment (*SS*) concentration was determined by filtering a predetermined volume of water sample through a GF/F glass fiber filter. Before filtration, the filter was heated at 550°C for 4 h and then dried to constant weight at 105°C after filtration. The concentration of *SS* was determined from the difference in masses of the filter without and with sediment and the volume of the water sample used for filtration. To determine the organic matter content in the suspension, the filter with the filtration and drying residue was heated at 550°C for 4 h. The OM_{SS} content was calculated from a relationship derived from ignition losses during heated [ZHU *et al.* 2015]. For laboratory analyses, water samples were collected from approximately 20–50 cm below the surface of the water table and transported in plastic containers of approximately 2 dm^3 in mobile refrigerators to the laboratory.

Spectrophotometric determinations of total phosphorus (TP_W) and chlorophyll *a* (Chl*a*) were also conducted in the collected reservoir water samples. Total phosphorus concentration (TP_W) was determined after mineralisation in the presence of H_2SO_4 and peroxodisulphate(VI). In turn, Chl*a* concentration was determined in samples after heat extraction with ethanol. An Aquamate spectrophotometer (Thermo Scientific) was used for spectrophotometric analyses. In addition, total nitrogen (TN_W) concentration was determined using a TOC-VCPN analyzer (Shimadzu).

Statistical analysis

Statistical interpretation of the obtained results was performed using Statistica 13.0 PL program. Basic descriptive statistics of the obtained results were determined: minimum value (min), maximum value (max), arithmetic mean ($\bar{x}$) and standard deviation (σ). Also analysed were the results of the Kruskal–Wallis ANOVA test (ANOVA KW), as well as Pearson's linear correlation matrices (r). These analyses assessed whether the relationship or differences between the selected parameters were statistically significant. Principal component analysis (PCA) was used to identify those variables that have a strong influence on the appearance of the other components, i.e. those that form a homogeneous group. The validity of using PCA analysis was checked by analysing the obtained correlation matrices using Bartlett's test and Kaiser–Mayer–Olkin coefficient. The level of significance was assumed for the study $\alpha = 0.05$.

RESULTS AND DISCUSSION

INDICATORS CHARACTERISING BIOGENIC CONDITIONS IN THE STUDIED RESERVOIRS

The values of total phosphorus (TP_W) concentrations in the Blizne Reservoir waters at individual study sites did not show statistically significant differentiation (ANOVA KW, $p = 0.49$, $p > \alpha$). The values of this parameter were varied from 0.03 to 0.07 $mg \cdot dm^{-3}$ (Fig. 2a). The mean TP_W value at each site was 0.05 $mg \cdot dm^{-3}$ (Tab. S1). The spatial distribution of total nitrogen (TN_W) concentration values also showed no statistically significant differences (ANOVA KW, $p = 0.59$, $p > \alpha$). During the analysis period values of this parameter ranged from 0.42 to 0.64 $mg \cdot dm^{-3}$ (reservoir mean 0.54 $mg \cdot dm^{-3}$), and mean TN_W values at individual study sites were very similar (0.52–0.56 $mg \cdot dm^{-3}$) – Table S1.

The obtained TP_W values in Maziarnia Reservoir waters showed statistically significant variation among the sites (ANOVA KW, $p = 0.02$, $p < \alpha$). Mean values at the analysed sites ranged from 0.08 to 0.19 $mg \cdot dm^{-3}$ (Table S2), and the mean TP_W value in the reservoir during the considered period was 0.13 $mg \cdot dm^{-3}$. The

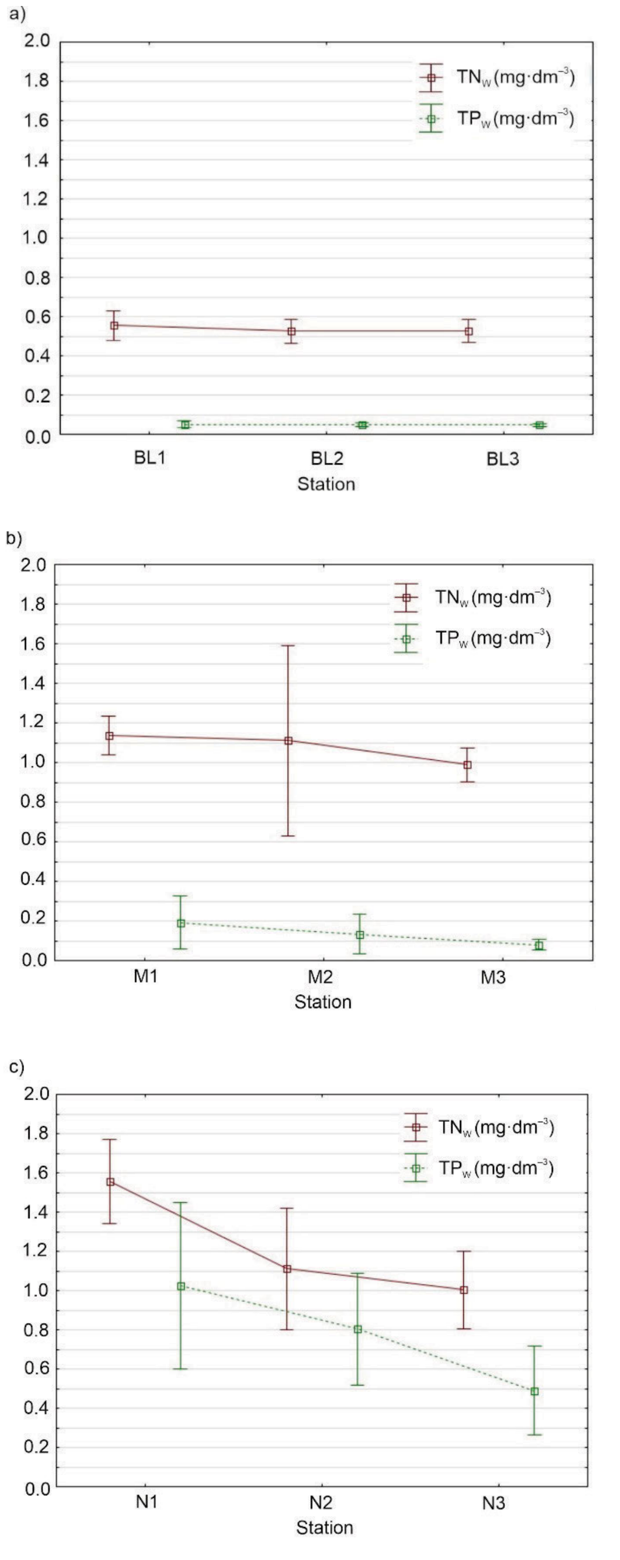

Fig. 2. Distribution of mean concentrations (with confidence intervals) of total phosphorus (TP_W) and total nitrogen (TN_W) in waters of the studied reservoirs: a) Blizne, b) Maziarnia, c) Nielisz; source: own study

direction of spatial changes in TP_W concentrations showed a decreasing trend from the river zone of the reservoir to the site located at the dam (M3). In turn, in the case of total nitrogen (TN_W) concentrations, no statistically significant spatial variation was found (ANOVA KW, $p = 0.07$, $p > \alpha$). For the most part of the analysed period, concentrations of this biogen in reservoir waters were at a fairly stable level (Fig. 2b). In the analysed period, values of this parameter oscillated within the range from 0.87 to 2.04 mg·dm^{-3}, and mean TN_W values at individual sites were at a very similar level (from 0.99 to 1.14 mg·dm^{-3}, mean for the reservoir 1.08 mg·dm^{-3} (Tab. S2).

In the case of Nielisz Reservoir, significant distances between the research sites (from about 3–5 km) significantly determined the distribution of obtained TP_W values (ANOVA KW, $p = 0.03$, $p < \alpha$). Mean values of this parameter at the designated sites ranged from 0.49 to 1.02 mg·dm^{-3} (reservoir mean 0.77 mg·dm^{-3}) – Table S3. Similar to Maziarnia Reservoir, it was noted that TP_W concentration values tended to decrease from the site in the river zone of the reservoir to the site at the dam. The spatial distribution of TN_W values, similarly to TP_W showed significant variation (ANOVA KW, $p = 0.02$, $p < \alpha$). Mean TN_W values at individual sites ranged from 1.00 to 1.56 mg·dm^{-3} (reservoir mean 1.22 mg·dm^{-3}) – Table S3. Similarly to TP_W, it was observed that TN_W values generally showed a decreasing trend from the reservoir river zone towards the dam. For TN_W variability over time, the situation was generally similar to that for TP_W (Fig. 2c).

PHYTOPLANKTON BIOMASS INDICATOR

Determined concentrations of Chl*a* in water sampled from respective study sites in Blizne Reservoir did not show statistically significant differentiation (ANOVA KW, $p = 0.16$, $p > \alpha$) and ranged from 3.7 to 25.9 μg·dm^{-3} (Tab. S4). The highest values were recorded in the river zone of the reservoir and the lowest in the dam zone (Fig. 3a).

In Maziarnia Reservoir, as in the case of Blizne Reservoir, Chl*a* concentration values did not show statistically significant differences between sites (ANOVA KW, $p = 0.53$, $p > \alpha$). Mean Chl*a* values at individual sites ranged from 29.7 to 66.0 μg·dm^{-3} (Tab. S5). The highest Chl*a* values were recorded in the central region of the reservoir (M2) and the lowest at the site located near the dam (Fig. 3b). An incidental spike in Chl*a* values of 236.9 μg·dm^{-3} was also recorded at site M2 (11th September 2018). Other water parameters also reached maximum values during this period (Tab. S1).

The range of mean Chl*a* concentrations recorded at the designated sites in Nielisz Reservoir ranged from 75.9 to 116.3 μg·dm^{-3} (Tab. S6). Similarly to the other reservoirs, no statistically significant spatial differentiation of this parameter was found (ANOVA KW, $p = 0.22$, $p > \alpha$). The highest values of Chl*a* were recorded in the river zone of the reservoir and the lowest at the site located near the dam (Fig. 3c).

QUANTITATIVE ANALYSIS OF SUSPENDED SEDIMENT AND ORGANIC MATTER IN THEM

The analysis of the obtained concentrations of suspended sediment (SS) in the waters of the studied reservoirs (Tabs. S7–S9) showed their significant variation. The results of the Kruskal–Wallis rank ANOVA test showed that reservoir parameters (e.g. reservoir capacity) significantly determined the distribution of suspended sediment concentrations in their waters (ANOVA KW, $p = 0.0000$, $p < \alpha$). Mean suspended sediment concentration in Blizne Reservoir was 12.07 mg·dm^{-3} (total reservoir capacity 0.137 mln m^3), while in Maziarnia Reservoir it was 14.75 mg·dm^{-3}

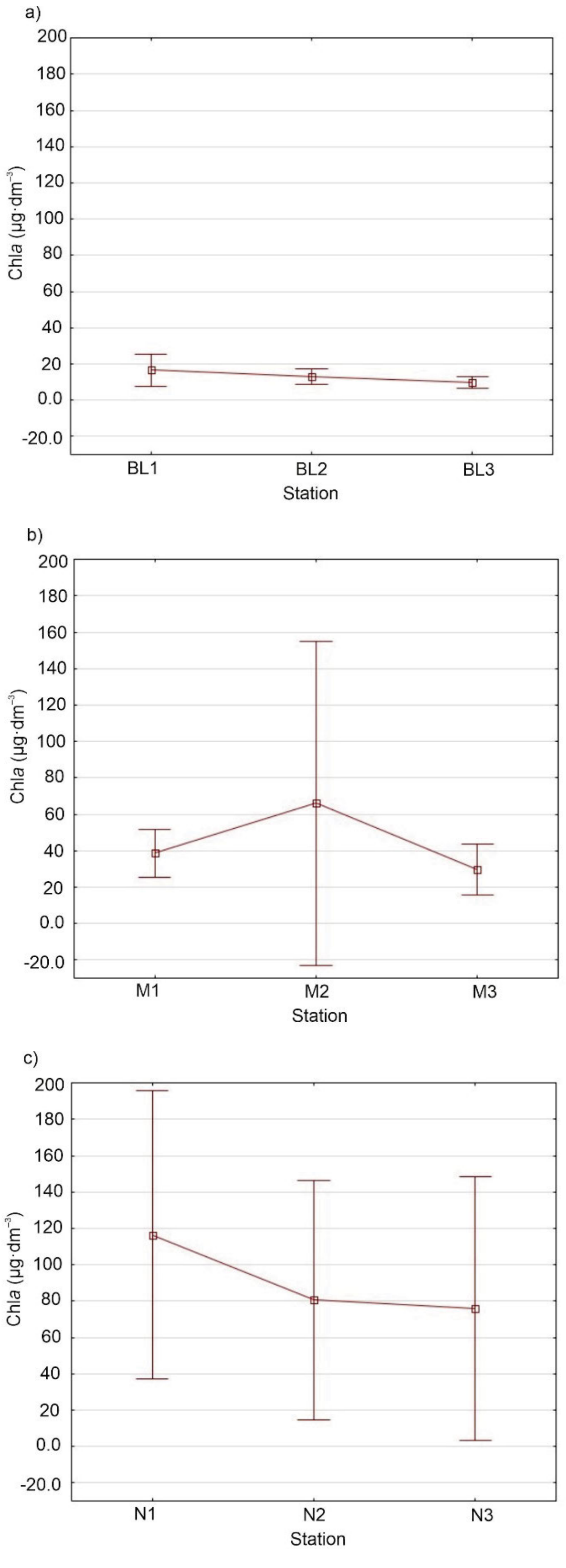

Fig. 3. Distribution of mean values (with confidence intervals) of Chl*a* in waters of the studied reservoirs: a) Blizne, b) Maziarnia, c) Nielisz; source: own study

(total reservoir capacity 2.75 mln m^3). Mean suspended sediment concentration in Nielisz Reservoir was 34.15 mg·dm^{-3} (total capacity reservoir 20.61 mln m^3). Taking into account distribution of SS concentrations obtained in waters of the studied reservoirs, a tendency common for all sites was observed for SS concentration to increase in the river zone (in relation to the level at the point on the river upstream of the reservoir) and its gradual reduction with water flow through the reservoir (Fig. 4). Spatial

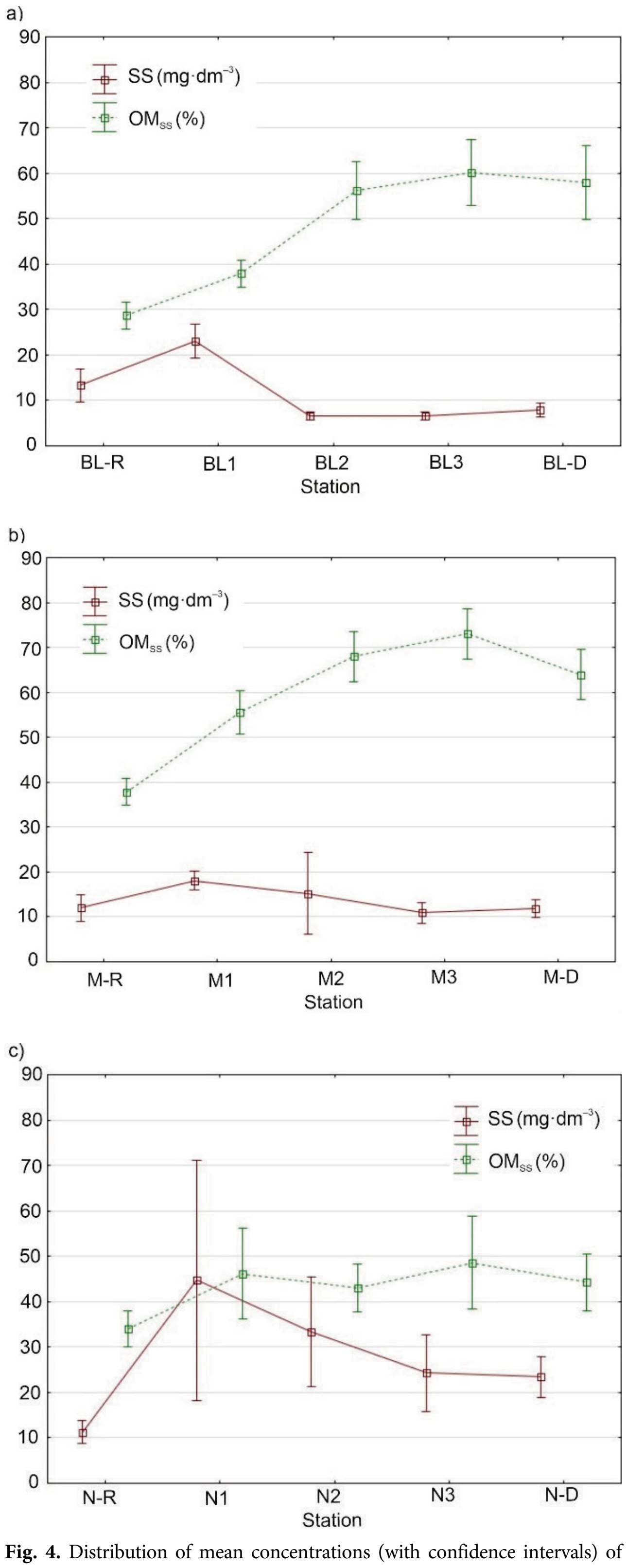

Fig. 4. Distribution of mean concentrations (with confidence intervals) of suspended sediment (*SS*) in waters of studied reservoirs and their organic matter content (OM_{SS}): a) Blizne, b) Maziarnia, c) Nielisz; source: own study

differentiation of this parameter was confirmed by the results of ANOVA KW test, where for Blizne and Nielisz Reservoir p = 0.0000, $p < \alpha$, and for Maziarnia reservoir p = 0.0006, $p < \alpha$. Mean SS values in Blizne Reservoir at sites BL1, BL2, and BL3 were 23.03, 6.55, and 6.62 mg·dm^{-3}, respectively (Tab. S7). A slightly different distribution of mean SS concentration values was obtained in Maziarnia Reservoir: 18.13, 15.23, and 10.09 mg·dm^{-3} (for M1, M2, and M3, respectively) – Table S8. The highest mean SS concentrations were recorded in Nielisz Reservoir 44.71, 33.39, and 24.34 mg·dm^{-3} (for sites N1, N2, and N3, respectively) – Table S9.

Suspended sediment concentration values in river waters at sites located upstream of reservoirs showed no statistically significant variation (ANOVA KW, p = 0.80, $p > \alpha$). Mean *SS* values at the BL-R, M-R, and N-R measurement sites were 13.34, 12.01, and 11.26 mg·dm^{-3}, respectively (Tabs. S7–S9). The distribution of suspended sediment concentrations in river water, at sites downstream of the dam of each reservoir (BL-D, M-D, and N-D), was closely related to reservoir conditions (ANOVA KW, p = 0.0000, $p < \alpha$). The average suspended sediment concentrations at these sites were 7.82, 11.85, and 23.42 mg·dm^{-3} (BL-D, M-D, and N-D, respectively) – Tables S7–S9. These values were similar to *SS* concentrations in reservoirs at sites located in the dam zone (BL3, M3, and N3) – Tables S7–S9. In the case of Nielisz Reservoir, much higher *SS* concentrations were obtained in river waters downstream the dam with respect to concentrations recorded at the upstream site (Fig. 4c), comparable for Maziarnia Reservoir (Fig. 4b), and much lower for Blizne Reservoir (Fig. 4a).

Changes in suspended sediment concentrations significantly negatively correlated with organic matter content (OM_{SS}) (r = –0.42, $p < 0.05$, n = 105). At lower concentrations of *SS* in the waters of reservoirs, higher contents of OM_{SS} were observed (Fig. 4). In the case of Blizne and Maziarnia Reservoirs, significant OM_{SS} variations were observed along the longitudinal axis of the reservoirs, and the direction of OM_{SS} changes coincided with the direction of water flow (from the river zone to the dam). In this case, the variation of this parameter was confirmed by the results of ANOVA KW test, where for Blizne Reservoir p = 0.0000, $p < \alpha$, and for Maziarnia Reservoir p = 0.0002, $p < \alpha$. The highest mean OM_{SS} values in these reservoirs occurred at site BL3 and M3 i.e. in the dam area (60.23% and 73.02% respectively) – Tables S7 and S8. However, in Nielisz Reservoir no clear trend in changes in OM_{SS} content was found between sites (ANOVA KW, p = 0.73, $p > \alpha$). Mean values of this parameter remained at a similar, constant level (ranging from 43.06% to 48.62%) – Table S9. Similar to *SS*, significant variation in OM_{SS} content was observed between the study reservoirs (ANOVA KW, p = 0.0000, $p < \alpha$). Statistical analysis showed that reservoir parameters (e.g., water retention time) could significantly determine the distribution of OM_{SS} values obtained, but the relationship was inverse to that for *SS*.

Also, the variability of OM_{SS} contained in *SS* in river water at sites downstream of the reservoir dam was significantly related to individual reservoir parameters (ANOVA KW, p = 0.001, $p < \alpha$). The mean organic matter contents (OM_{SS}) at sites BL-D, M-D and N-D were 57.92, 63.92 and 44.26%, respectively (Tabs. S7–S9), which almost corresponded to the mean values obtained at sites located in the dam zone (BL3, M3 and N3). An increase in OM_{SS} values was also observed at sites downstream of the reservoirs with respect to values obtained at upstream sites (BL-R – 28.71%, M-R – 37.86% and N-R –33.98%) – Tables S7–S9, Figure 4. For Nielisz Reservoir, this was a statistically significant (ANOVA KW, p = 0.007, $p < \alpha$) but relatively small increase, and for the other reservoirs it was very pronounced and also statistically significant (ANOVA KW, p = 0.0000, $p < \alpha$). Also, principal component analysis (PCA) confirmed that water retention time (T_r), had a significant effect on the distribution of OM_{SS} content at each study site (Fig. 5).

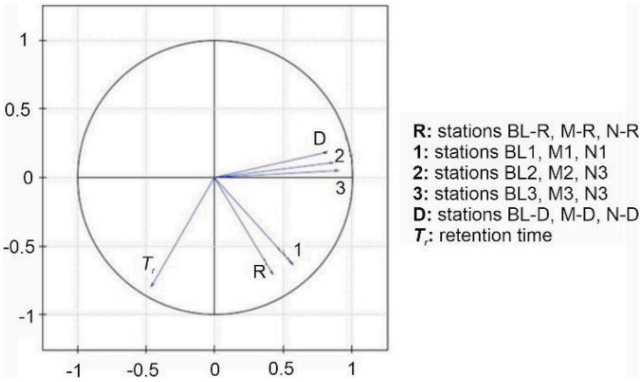

Fig. 5. Results of principal component analysis (PCA); the effect of water retention time (T_r) in the reservoirs on the concentration of organic matter (OM_{SS}) contained in suspended sediment (*SS*); source: own study

The results of Bartlett's test statistic ($p < 0.000001$) and the determined Kaiser–Mayer–Olkin coefficient (0.67) indicate that the hypothesis of a significant difference between the obtained correlation matrix and the unit matrix, that is, a significant correlation of the variables. Finally, the indications for principal component analysis were considered sufficient. The vectors for organic matter content (OM_{SS}) at sites located on the river upstream of the reservoirs (R) and at sites in the river zone of the reservoirs (1) were marginally correlated with water retention time in reservoirs (T_r), as evidenced by the angle between these parameters (close to a right angle). On the other hand, the angle between the vectors representing organic matter content (OM_{SS}) between the other sites is in the range of 90–180° indicating that there is a strong (but negative) correlation between these variables.

DISCUSSION

A set of biological and physicochemical processes resulting in deterioration of water quality and reduction of utility and landscape values leads to the degradation of water ecosystems. It is also believed that a direct cause of the progressive degradation of surface waters is the introduction of excessive loads of pollutants (e.g. nutrients) to rivers and water reservoirs. Excessive nutrient concentrations in water can lead to imbalance in the production and decomposition of organic matter and its deposition to the bottom of the reservoir. If such a state persists for a sufficiently long time, it may lead to eutrophication of waters, oxygen deficit and favourable conditions for development of organisms. Periodic intense phytoplankton blooms may be a manifestation of this process [Cygan 2016; Miąsik *et al.* 2014; Sojka *et al.* 2016; 2017].

In some simplification, the concentration of chlorophyll *a* in water represents the amount of phytoplankton biomass and consequently, also the productivity and trophic state of the water reservoir. Phytoplankton growth in water depends, among other things, on the availability of nitrogen and phosphorus in the water [Siemieniuk *et al.* 2015]. It is assumed that phosphorus concentrations above 0.02 mg·dm^{-3} in water and 0.3 mg·dm^{-3} in the case of nitrogen are sufficient for favourable conditions for excessive phytoplankton growth to occur [Jachniak, Jaguś 2011; Vollenweider 1968]. The obtained results showed that in the waters of the studied reservoirs the values of phosphorus and nitrogen concentrations exceeded the cited values. In Maziarnia and Nielisz reservoirs the values of total phosphorus concentrations were much higher than 0.1 mg·dm^{-3}, and in the case of total nitrogen – above 0.3 mg·dm^{-3}. The mean value of TP_W obtained in Nielisz Reservoir (0.77 mg·dm^{-3}) was the highest of all the analysed reservoirs (mean in Blizne Reservoir – 0.05 mg·dm^{-3}, Maziarnia Reservoir – 0.13 mg·dm^{-3}). The lowest TP_W concentrations in Blizne Reservoir (in comparison with the remaining analysed reservoirs) were also reflected in the lowest mean concentrations of chlorophyll *a* (Chl*a*) (Blizne – 13.2 μg·dm^{-3}; Maziarnia – 44.7 μg·dm^{-3}; Nielisz – 90.9 μg·dm^{-3}). Similarly to TP_W concentration, mean TN_W value in Nielisz Reservoir (1.22 mg·dm^{-3}) was the highest of all analysed reservoirs (Blizne Reservoir – 0.54 mg·dm^{-3}, Maziarnia Reservoir – 1.08 mg·dm^{-3}). Statistically significant correlation between Chl*a* values and concentrations of TP_W and total nitrogen in water (TN_W) was also found in all studied reservoirs. For Maziarnia Reservoir the correlation coefficient between Chl*a* and TP_W was $r = 0.56$, $p < 0.05$, $n = 18$, for Nielisz Reservoir $r = 0.60$, $p < 0.05$, $n = 12$, while for Blizne Reservoir $r = 0.68$, $p < 0.05$, $n = 18$. In the case of correlation between Chl*a* and TN_W it was respectively for reservoir: Blizne $r = 0.62$, $p < 0.05$, $n = 18$, Maziarnia $r = 0.90$, $p < 0.05$, $n = 18$ and Nielisz $r = 0.72$, $p < 0.05$, $n = 12$. Moreover, a statistically significant correlation between TP_W values and total nitrogen concentration in water (TN_W) was found in all studied reservoirs: for Blizne Reservoir $r = 0.59$, $p < 0.05$, $n = 18$; Maziarnia Reservoir $r = 0.64$, $p < 0.05$, $n = 18$ and Nielisz $r = 0.80$, $p < 0.05$, $n = 12$.

It was also observed that in much larger reservoirs (Maziarnia and Nielisz), compared to Blizne Reservoir, there was a clear trend of decreasing TP_W and TN_W values in the direction from the reservoir river zone to the dam. This variability suggests that the nutrients that fed these reservoirs with the river flow were consumed in the primary production process in the lower parts of reservoirs (Fig. 3b, c). However, in the smallest Blizne Reservoir this trend was not as pronounced as in Maziarnia and Nielisz Reservoirs. This may indicate that in small reservoirs (rheolimnic reservoirs) a certain pool of phosphorus does not participate in the internal production process as it is discharged with the outflow. It is estimated that in flow-through reservoirs only 20% of the inflowing nutrient load can be incorporated into the trophic chain [Tomaszek, Koszelnik 2003]. The correlations obtained between the analysed parameters may also suggest that the larger Maziarnia and Nielisz reservoirs witnessed intensive development of aquatic organisms using phosphorus and nitrogen compounds in the processes of their own growth mechanisms [Wojtkowska, Dmochowski 2009]. An important element in this process could be biological transformation of phosphorus compounds, which is highly dependent on biochemical transformations of carbon and nitrogen [Tarnawski *et al.* 2012]. As a result of supplying reservoirs with nutrient loads disproportionate to demand, the fertility of their waters increases. If such a state persists for a long time, it causes excessive growth of phytoplankton and rooted aquatic vegetation. This, in turn, may lead to negative consequences for the reservoir, including excessive accumulation of organic matter, increased demand for oxygen necessary for its decomposition, as well as water alkalisation. Moreover, intensive growth of phytoplankton contributes to significant increase in water turbidity and unfavourable changes in its organoleptic properties. Shallow water bodies can exist in two contrasting states: a clear-water state with dominance of submerged macrophytes or a turbid-water state with dominance of phytoplankton. Once the reservoir condition converts to the turbid-water condition and is perpetuated in subsequent years, the transition back to the clear-water condition is very difficult and requires advanced restoration efforts. To restore a macrophyte-dominated state, nutrient loading must be reduced to below the level where the transition to a turbid-water state previously occurred [Blindow *et al.* 2014; Dokulil, Teubner 2003; Peckham *et al.* 2006; Scheffer 1998]. Due to the deterioration of light conditions caused by the persistent turbid state over a long period of time, the death of submerged aquatic vegetation may occur [Gałczyńska, Buśko 2016; Pełechaty, Pronin 2015]. This is an unfavourable phenomenon for the environment, because macrophytes submerged in water perform a number of useful functions. Co-competing for nutrients, they are natural competitors for phytoplankton. They regulate the concentration of nitrogen and phosphorus compounds in water by assimilating them in their tissues. In addition, they form a natural biogeochemical barrier that, on the one hand, reduces the resuspension of bottom sediments and, on the other hand, effectively stops the migration of mineral substances from the catchment, thus reducing their impact on reservoir water quality [Blindow *et al.* 2014; Borics *et al.* 2012; Pełechaty, Pronin 2015; van Donk, van de Bund 2002].

A very important role in the mass growth of phytoplankton, in addition to the presence of major nutrients in the water, is also played by the availability of carbon compounds. To some approximation, the organic matter content can express the amount of organic carbon present in the studied ecosystem [Pietrzyk, Papciak 2016]. The export of total organic carbon (both in particulate and dissolved form) from terrestrial to aquatic ecosystems carries important implications for water quality and its global cycling [Derrien *et al.* 2019; Glendell, Brazier 2014]. Most often, carbon in organic form is released through biodegradation or photodegradation, which affects water quality as well as the degree of eutrophication [Derrien *et al.* 2019; Palviainen *et al.* 2016].

Analysis of organic matter content (OM_{SS}) in waters of three reservoirs differing in retention time showed that this parameter significantly determined the distribution of OM_{SS} values obtained. In Blizne and Maziarnia reservoirs, organic matter content (OM_{SS}) fluctuations were significantly differentiated along the longitudinal axis of the reservoirs, and the direction of OM_{SS} changes was consistent with water flow direction, which could be related to the progressing production of autochthonous organic matter. As organic carbon found in suspended organic matter is an important source of energy it specifically integrates both physical, chemical and biological characteristics of aquatic ecosystems [Hanson *et al.* 2003; Solomon *et al.* 2015; Wiegner, Seitzinger 2001]. It affects the food web structure of the ecosystem and thus the transparency and thermal stratification of reservoir waters [JANSSON *et al.* 2000; KANKAALA *et al.* 2010]. It also influences water chemistry (contributes to the carbonate-calcium balance), and is responsible for the mobility, toxicity and bioavailability of organic pollutants [AKKANEN *et al.* 2004; BUFFAM *et al.* 2008; KINDLER *et al.* 2011]. However, as the results of our study indicate, larger reservoirs are more resistant to the degradative effects of organic carbon. In the largest reservoir Nielisz, there was no clear trend of change in OM_{SS} content between sites, which may indicate that the reservoir has developed some kind of defense mechanism against pollutants that may degrade its water quality. Moreover, the smaller reservoirs had significantly higher OM_{SS} contents in sediments suspended in their waters (Blizne – 51.44% and Maziarnia – 65.51%) than the much larger Nielisz Reservoir (45.96%). This suggests that in the case of small reservoirs the average retention time of water (from 18 to 36 days) is long enough for intensive internal production of matter to occur, but too short for it to be balanced by mineralisation and sedimentation processes. Also, transit character of Blizne and Maziarnia reservoirs could significantly limit effectiveness of self-purification process. On the other hand, Nielisz Reservoir is clearly larger than the remaining reservoirs (average water retention time is 77 days), which might have a positive effect on the degree of mineralisation of matter suspended in its waters. In large and deep reservoirs, the transport of organic matter to the bottom takes place over a longer interval of time, so the process of its mineralisation is more efficient than in small and shallow reservoirs [ČESONIENĖ *et al.* 2020; WOJTKOWSKA, DMOCHOWSKI 2009].

Also, the organic matter content (OM_{SS}) of suspended sediment in the waters of rivers downstream of the dam (BL-D, M-D and N-D) was related to the conditions of the reservoirs studied. An increase in OM_{SS} content was observed at all study sites in relation to sites located in rivers upstream of the reservoir (BL-R, M-R and N-R). It was observed that the way water was discharged from the reservoirs could determine the concentration of organic matter (OM_{SS}) contained in suspended sediment in rivers downstream of the dam (BL-D, M-D and N-D). In Maziarnia and Nielisz Reservoirs where water was discharged through a lower outlet a significant reduction in OM_{SS} content was observed compared to sites located near of the dam (BL3, M3, N3). On the other hand, in Blizne Reservoir, where water is discharged through an upper overflow, OM_{SS} reduction was not as pronounced as in the remaining studied reservoirs. The nature of organic matter is constantly changing during transport to the reservoir and falling in the water column and after deposition on the bottom [TARNAWSKI *et al.* 2012; WOJTKOWSKA, DMOCHOWSKI 2009]. In reservoirs where water is discharged through the upper overflow, organic material is exposed to oxidation processes occurring in the water for a shorter time. As a result, the process of water self-purification occurs less efficiently than in facilities where water is discharged through the lower outlet. Thus, the use of lower outlet considerably lengthens the path of material fall in the water column, as a result of which the process of organic matter decomposition may take place for a longer time. It follows that this type of solution carries favourable effects related to the possibility of reducing the negative effects of river partitioning by a hydrotechnical structure.

Similarly to organic matter content (OM_{SS}), analysis of suspended sediment (*SS*) concentrations in waters of the studied reservoirs showed that water retention time significantly determined the distribution of *SS* values obtained. The lowest mean *SS* concentration was recorded in the smallest Blizne Reservoir (retention time 18 d), and the highest in the largest Nielisz Reservoir (retention time 77 d). The more transient nature of the Blizne Reservoir (frequently exchanging water) may have significantly impaired the ability to both grow plankton and retain products associated with internal recharge processes of suspended sediment. In all reservoirs studied, suspended sediment concentrations at sites located in the river zone (BL1 – 23.03 mg·dm^{-3}, M1 – 18.13 mg·dm^{-3}, N1 – 44.71 mg·dm^{-3}) were higher compared to levels obtained at sites located in the river upstream of the reservoir (BL-R – 13.34 mg·dm^{-3}, M-R – 12.01 mg·dm^{-3}, N-R – 11.26 mg·dm^{-3}). Suspended sediment (*SS*) concentrations were gradually reduced as they approached of the dam zone. The obtained *SS* concentrations at sites in the dam zone (mean BL3 – 6.62 mg·dm^{-3}, M3 – 10.90 mg·dm^{-3}, N3 – 24.34 mg·dm^{-3}) were at lower levels than those at sites in the river zone of the reservoirs (BL1, M1, N1). A characteristic feature of dammed reservoirs is their ability to permanently retain and deposit (accumulate) trailing and uplifted debris [BĄK *et al.* 2011]. As a result of this natural process, a significantly smaller load of suspended matter is usually transported to the dam zone (matter depletion phenomenon) [CIEŚLA *et al.* 2020b]. Sites located on rivers upstream of the reservoirs (BL-R, M-R and N-R) were characterised by similar *SS* concentrations (no statistically significant differences were found between suspended sediment concentrations in the waters of the studied rivers). On the other hand, the distribution of *SS* concentrations at sites in rivers downstream of dams (BL-D, M-D and N-D) depended on conditions in the reservoir. This thesis was confirmed by the results of the PCA analysis, which suggest that the duration of water retention in the studied reservoirs and the method of its discharge may have influenced water quality in rivers downstream of the dam. In the largest reservoir studied, Nielisz, an increase in *SS* concentrations was found at a site downstream of the dam relative to concentrations at a site upstream of the reservoir. In the smaller reservoirs of Blizne and Maziarnia the opposite situation was observed.

The concentration of suspended sediment in the waters of rivers and streams varies in a huge spectrum of values. In the network of rivers fed from mountain and foothill catchments, it usually reaches the level of a few mg·dm^{-3}. Definitely higher values, often exceeding 25 mg·dm^{-3}, are observed in the waters of lowland rivers. High concentrations of suspended matter in water may also have a seasonal character, associated with periodically occurring flood surges [NOCOŃ 2012]. In addition, the ability and conditions of transport are largely responsible for creating the level of suspended sediment concentration in the water body. The mechanism that enables the transport of sediments follows complex and irregular patterns and depends on many factors (including climate, meteorological conditions, land cover and slope), and among the most important are the erosive processes occurring within the catchment (which are the primary source of suspended sediment in rivers) [VERCRUYSSE *et al.* 2017]. Therefore, suspended sediment concentrations for the same river can vary by up to three orders of magnitude in a single year [CHAPMAN (ed.) 1996].

Despite the fact that suspended sediments are mainly identified with pollutants that can negatively affect the environment, in surface waters they are a natural and necessary element of properly functioning aquatic ecosystems [BRILS 2008]. They are also a key parameter necessary to understand and rationally control, among other things the sculpting processes of rivers (fluvial processes). The presence or absence of suspended sediment determines the erosive and depositional properties of rivers, and thus shapes the landscape and controls groundwater levels [Cieśla *et al.* 2020a]. Furthermore, for many rivers, high suspended sediment concentrations alone do not determine poor water quality, nor should maintaining low concentrations always be a primary goal in water resource management [Wagner 2019].

CONCLUSIONS

The artificial objects created on the river (dam reservoir), besides realising socio-economic aims, are also an important element of the landscape, enriching biodiversity in its surroundings (in the long run these objects become a habitat for many plant and animal species). On the other hand, to some extent, these objects may adversely affect the quality of the natural environment. It was shown that morphometric and hydrological parameters of reservoirs determine the level of suspended sediment (*SS*) concentration in water and organic matter (OM_{SS}) contained in them, both within reservoirs and in rivers downstream of dams. It was also shown that larger objects (such as Nielisz Reservoir) are more resistant to all biological and physicochemical processes resulting in worsening of water quality, increase in its trophy and reduction of utility and landscape values. Generally, reservoir resistance to degradation is understood as a set of reservoir features that enable it to resist the negative influence of external factors occurring in its catchment. These features include such parameters as mean depth, water exchange dynamics or the capacity to shoreline length ratio. It has been shown that in large and deep reservoirs the process of pollutant reduction is more efficient than in small and shallow reservoirs. In addition, the more flow-through nature of smaller reservoirs may significantly reduce the effectiveness of the self-purification process. The results also suggest that the use of lower outlet (discharge) of water from reservoirs can effectively reduce the negative aspects of hydrotechnical structures' impact on the natural environment. However, due to the fact that factors such as characteristics of the catchment, morphometric and hydrological parameters of reservoirs, climatic zone, or season can have a significant influence on the results of the study, caution should be exercised when comparing results obtained at other regions and for different objects.

FUNDING

The research referred to here was financed by Poland's National Science Centre, under Research Project No. 2017/25/B/ST10/00981.

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