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Variability of concentrations of phosphorus forms under the conditions of weir renovation – The Głuszynka river-lake system case study

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Abstract: To fill the knowledge gap on the functioning of the river-lake system during the modernisation of the weir, an analysis of the variability of selected physico-chemical indicators was carried out. In the parameter analysis, particular emphasis was placed on phosphorus (P) and orthophosphate(V) (OP) content in the hydrological year 2022 and water quality was compared before, during and after the maintenance work on the discharge weir. Physico-chemical parameters were analysed monthly at four stations. Concentrations of P and OP increased significantly as a result of the refurbishment works at the measurement point located downstream of the weir (P4), which contributed to the determination of a statistically significant change point. At the same time, when high P and OP contents were observed, high electrolytic conductivity and ammonium nitrogen in water were also recorded. The content of P and OP indicators was further reduced, but their content was still several times higher than before the renovation. The renovation of the weir below Lake Jeziory Wielkie contributed to a significant deterioration of water quality in the river-lake system. Due to the nature of this system, this was of great importance for the downstream reservoirs. The statistical analysis showed that the renovation of the weir below Lake Jeziory Wielkie contributed to a significant deterioration of water quality in the river-lake system.

Keywords: eutrophication, orthophosphate(V), phosphorus, river-lake system, weir

INTRODUCTION

According to the principles of the Water Framework Directive (WFD), the improvement of lake water quality (Directive, 2000) is very important. The aforementioned Directive is a challenge for all lakes, but especially for lakes, where it is impossible to eliminate all sources of pollution (Tekile, Kim and Kim, 2015; Arle, Mohaupt and Kirst, 2016; Dunalska *et al.*, 2018; Filipe *et al.*, 2019). Water quality has now become a major concern due to its multiple uses in the drinking, irrigation, and industrial sectors around the world. Hence, ensuring water quality is no doubt an important issue in maintaining sustainable living conditions for all, and the provision of clean water has been listed as an important goal among the 17 Sustainable Development Goals drafted by the United Nations (UN, 2015).

The river-lake system is unity because of the connection between the river and the reservoirs, which interact with each other, and rivers flowing through lakes can affect the water quality of the river (Wetzel, 2001; Klimaszyk *et al.*, 2015; O'Hare *et al.*, 2018; Kuriata-Potasznik, Szymczyk and Skwierawski, 2020). Lakes in the river-lake system receive and store plenty of water from precipitation and release it steadily, this plays a significant role in flood control for the downstream rivers, irrigation, as well as the nutrient substance and sediment deposited in the lake area while the water flows through a lake. Therefore, lakes in a river-lake system provide the necessary elements for plant growth and the important habitats for wildlife (Zhang *et al*., 2019). Lakes in the river-lake system are most often located in lowland areas and are usually shallow, non-stratified and eutrophic reservoirs that tend to contribute to the disruption of the natural continuum of the river and can thus contribute to changes in the hydrological, physico-chemical and biological parameters of the water (Ward and Stanford, 1983; Kufel and Kufel, 1997; Hillbricht-Ilkowska, 1999; Wetzel, 2001). Sometimes, in the case of river and lake systems, small hydro-technical structures (most often weirs) are created to slow down the flow or retain the water flowing through the system. Due to their high retention capacity, the use of such solutions has many benefits for the environment, but such devices nevertheless need to be upgraded after some time (Zhang *et al*., 2019). In river-lake systems, the magnitude of pollution is determined by the river flow, as organic matter is mineralised as a result of the sudden slowing down of the river flow, and with the deposition of supplied and newly formed suspended solids in the bottom sediments, the lake becomes a sink for pollution (Kufel, 1993; Pytka *et al*., 2013; Hatvani *et al*., 2017; Tian *et al*., 2017). However, over time, flowing lakes become overloaded with nutrients and turn into a source of pollution for downstream river waters. The transported material is merely processed and exported further downstream, which in turn causes the runoff waters to be further enriched with organic matter generated in the lake (Hillbricht-Ilkowska, 1999; Teodoru and Wehrli, 2005). This poses a threat not only to the river but also to downstream lakes. Maintaining the quality of river-lake systems in good condition is very difficult due to the processes taking place there, while due to the high rate of biological accumulation of phosphorus, the content of this component should be reduced. Sometimes certain activities, such as the construction or repair of damming facilities on a river, can disrupt this pattern and cause negative changes in water quality, thereby exacerbating eutrophication by disturbing the bottom sediment layer (Cha *et al*., 2013; Lee *et al*., 2018). Eutrophication negatively affects aquatic ecosystems and leads to a loss of biodiversity and changes in the structure of aquatic ecosystems, so controlling the availability of P in the environment is important to maintain the ecological balance of lakes in river-lake systems (Zhong *et al*., 2021).

Although the environmental impact of large retention dams is well known in the literature, knowledge about the ecological impact of the renovation of small hydrotechnical structures (Włodarczyk, 2006) on water quality in river-lake systems is still insufficient. This work therefore fills the gap in this area and will reveal problems resulting from the modernisation of the weir. This information is extremely important from the point of view of the WFD, which requires European Union Member States to maintain good-quality of surface waters. As most European rivers today are a mosaic of upstream and downstream sides of weirs that succeed each other in short geographical distances, information on the qualitative effects of weirs on these river sections is crucial for representative assessment of their ecological status and for conservation and restoration management (Mueller, Pander and Geist, 2011).

The purpose of this study is to analyse the water quality of the Głuszynka River with special attention to the section above Lake Jeziory Wielkie–lake–below Lake Jeziory Wielkie (2 measurement points located on the river, two points on the lake). Physico-chemical indicators were analysed, with particular emphasis on the P and OP contents for the hydrological year 2022, in which the weir was renovated downstream of Lake Jeziory Wielkie. Observation of water parameters at four points allowed analysis of changes in water quality. It was hypothesised that (1) the renovation activities carried out on the flowing lake will contribute to the deterioration of water quality, increasing P and OP concentrations below the weir, and (2) the performed treatments affect the water quality in the entire river-lake system below the renovated weir.

MATERIALS AND METHODS

The study area of 134 km^2 covered the central-western part of Poland in the catchment of the Głuszynka River (Fig. 1). According to the physical-geographical division of Poland it is located in the south of the Baltic Lakelands (Kondracki, 2002) and within the range of the Weichselian glaciation. The Głuszynka River is approximately 24 km long and is a left-bank tributary of the Kopla River. The source of the Głuszynka River is considered to be Lake Raczyńskie and flows in a northerly direction through the lakes: Łękno, Jeziory Małe, Jeziory Wielkie, Bnińskie, Kórnickie, Skrzynki Duże and Skrzynki Małe (Fig. 1) (Janicka *et al*., 2022).

Lake Jeziory Wielkie is a fishing spot located in the forest, which is a natural refuge for fish such as carp and grass carp. For several years, the reservoir was used by the then Poznań Agricultural University (currently the University of Life Sciences in Poznań) as a research centre and was not open to fishing.

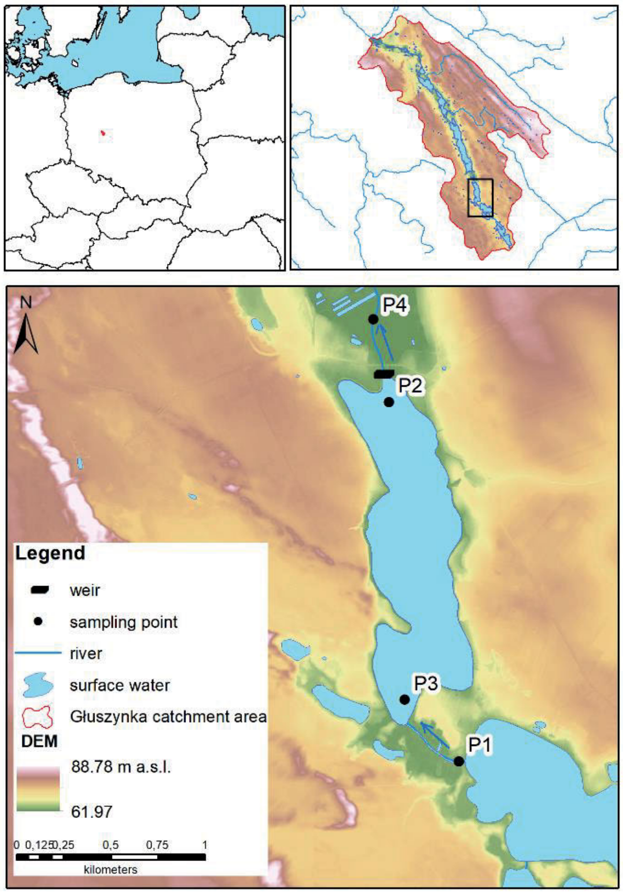

Fig. 1. Location of the study area; P1–P4 = sampling points; source: own elaboration

Currently, since 2006, the fishery has been opened as a special fishery with 22 fishing spots. The impact of fishing on lake ecosystems is expressed not only in the littering of the littoral and the destruction of shore and littoral habitats but above all in the increased supply of nutrients caused by the use of baits. Such a supply is estimated at 156 g of nitrogen and 28.8 g of P provided by one angler in one day (Szyper and Gołdyn, 2002). As a result, the P load may be high and in this case, the average may be as much as 133 kg per season (season lasts from April 1 to October 31).

The weir, located downstream of the lake, was modernised during the research conducted. The modernisation was commissioned by Wody Polskie, and information about the modernisation of the weir was published on the Miłosław Fishing Farm's social profile on Facebook platform (Pol. Gospodarstwo Rybackie Miłosław) on May 2, 2022. Renovation works began on May 4, 2022, and were completed on May 19, 2022. During the renovations, the lake wasn't emptied, but a cofferdam was made of sandbags on the upper (distance 5 m) and lower (distance 9 m) sides of the weir, 1.5 m high. During the work, water was passed through a steel pipeline, which could significantly affect the monitored physico-chemical indicators. Renovation works changed the speed of water flow, disturbing the natural flow of water in the river. This change could lead to changes in parameters determining water quality. In addition, disruption caused by weir renovation may hurt fish and other aquatic life (Mueller, Pander and Geist, 2011; Kiraga *et al.*, 2023). The renovation works included filling in gaps in the concrete structure and reinforcements, as well as repairing the cracked left wing of the abutment from the upper water side and replacing the tilt hatch. The renovations were aimed at restoring the full technical efficiency of the building. The works also included mowing the slopes and mechanical desilting of the river bottom (Wody Polskie, 2021).

In the hydrological year 2022, water samples for chemical analysis were collected monthly from four points, they were marked with the alphanumeric code (P1–P4): in point P1 (52°09'73.423"N; 17°07'47.921"E) – above Lake Jeziory Wielkie; points P2 (52°10'03.500"N; 17°07'57.900"E) and P3 (52°10'59.300"N; 17°07'45.200"E) – in Lake Jeziory Wielkie, point P4 (52°10'99.450"N; 17°08'47.572"E) – below Lake Jeziory Wielkie. At the outflow from Lake Jeziory Wielkie, a rectangular trigger weir is located (between points P3 and P4) – Figure 1. The water samples were collected in 1 dm^3 polyethylene bottles which were transported afterwards at the temperature of 4°C and analysed in the laboratory within 48 h of their collection. Water samples were analysed at the Laboratory of the Department of Land Improvement, Environmental Development and Spatial Management, the Poznań University of Life Sciences (Pol. Laboratorium Katedry Melioracji, Kształtowania Środowiska i Gospodarki Przestrzennej).

As part of the laboratory work, analyses of parameters such as P, OP, dissolved oxygen (DO), biological oxygen demand (BOD_5), chemical oxygen demand (COD), temperature (*T*), electrical conductivity (*EC*), pH, chlorides (Cl^-), carbonates ($H\text{-}CO_3^-$), nitrates: NO_3-N, NO_2-N, NH_4-N, nitrogen (N), iron (Fe) and sulphur (SO_4^{2-}) (Tab. S1 shows: range, mean, variability). Analyses were performed in duplicate each time, and data were presented as averages. However, special emphasis was placed on the content of P and OP in water. The concentration of P and OP was determined according to the method EN ISO 6878:2004. The content was measured using ammonium molybdate and ascorbic acid at 700 nm on a JENWAY instrument (7315 Spectrophotometer). However, P content was determined after mineralisation with $(NH_4)_2S_2O_8$. Other physico-chemical indicators that are important in terms of changes in surface water such as *EC*, N-NH_4 and pH were also analysed, for which worrying fluctuations were also observed. ELMETRON's CC-105 and CP-105 portable instruments were used for *EC* and pH analyse (*in situ*). In contrast, NH_4-N was determined spectrophotometrically on a MERCK NOVA60. In addition, the OP content was compared with the applicable European Communities (Surface Water) Objectives Regulations 2009 (Statutory Instrument, 2009). However, the European regulations do not refer to limit values for P, NH_4-N, *EC* and pH.

The analysed concentrations of the physico-chemical indicators are presented graphically using Statistica 13.3 (TIBCO Software Inc., Palo Alto, CA, USA). Furthermore, the parametric statistical change point analysis (the type of change point for mean and variance) was performed using the R program (R Development Core Team, 2019). This analysis was used to show the variability of the parameters due to the renovation work.

RESULTS AND DISCUSSION

The content of OP in the analysed measuring points in the hydrological year 2022 ranged from 0.01 to 2.89 (mg OP)$\cdot dm^{-3}$ (Fig. 2, Tab. S1). The analysis of the physico-chemical results of OP shows that, according to the regulation, the limit values for good water status (0.04 $mg\cdot dm^{-3}$) were significantly exceeded in 85% of the samples taken. The highest concentrations of OP were found in P4, below Lake Jeziory Wielkie (below the weir), their content was 2.89 (mg OP)$\cdot dm^{-3}$ (May 26, 2022 i.e. a week after the completion of the weir renovation works). According to Janicka *et al.* (2022), the average content of OP in 2016–2018 didn't exceed 0.36 $mg\cdot dm^{-3}$, and the maximum content of OP in this period, at the point below Lake Jeziory Wielkie was 0.55 $mg\cdot dm^{-3}$. When analysing the variance of this parameter at all points, it was noted that the greatest variability concerned measurement point P4, where the variance was 137.68%. For the remaining measurement points, the variance ranged from 61.54–116.67%.

However, when analysing the content of P, a fluctuation of this parameter from 0.02 to 3.04 (mg P)$\cdot dm^{-3}$ was observed. The average content of P in the analysed points was 0.47 (mg P)$\cdot dm^{-3}$. For this parameter, high variability was observed at point P1, and the variance was 136.36%. As in the case of OP, the extreme for P was observed in May 2022, it was 3.04 $mg\cdot dm^{-3}$. This value exceeds the content of P 7 times in 2016–2018 (Janicka, 2020) (Fig. 2, Tab. S1).

At the same time, when high P and OP contents were observed, high *EC* and NH_4-N in water were also recorded, amounting to 854 $\mu S\cdot cm^{-1}$ and 2.07 $mg\cdot dm^{-3}$, respectively in *EC* and NH_4-N. These were the highest values for these two parameters during the period analysed. During May, the content of these indicators should be reduced due to the vegetation taking place during this period, in favour of the development of primary producers. The water pH during the measurements on that day was 7.8 and was lower than the pH in the previous month, which may indicate that the concrete mixture used does not influence the water pH, and thus on the OP and P content of the water (Fig. 3, Tab. S1).

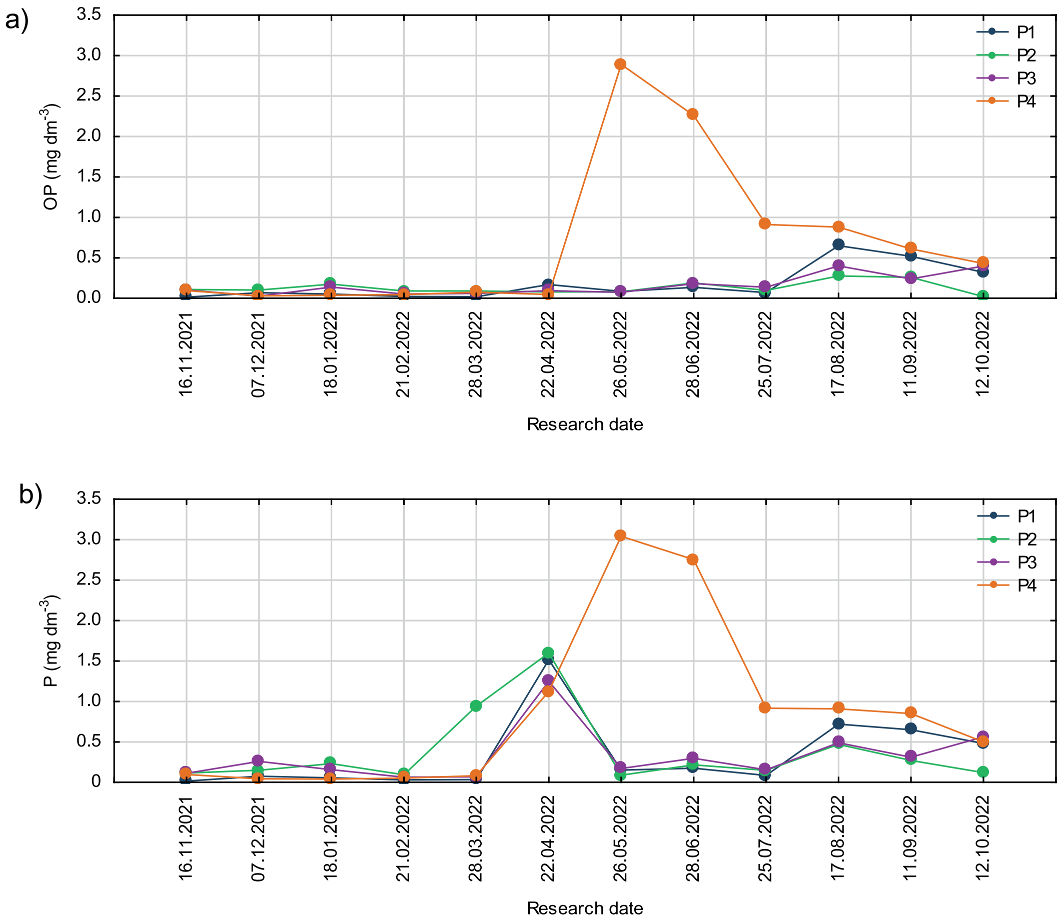

Fig. 2. Temporal variability of water in the hydrological year 2022: a) orthophosphate(V) (OP), b) phosphorus (P); P1–P4 as in Fig. 1; source: own study

As part of the work, a statistical analysis of the OP and P change points was performed, which showed a statistically significant change point, taking into account both the mean values and the variance of the data for all four measurement points. This analysis showed a statistically significant point of change only in the case of point P4 located downstream of the weir. The point of change in case P was a sample taken in April 2022, before the commencement of renovation works. This statistically significant variability shown in the change point analysis could be caused by the atmospheric precipitation that occurred in the last week preceding sampling, amounting to nearly 40 mm. According to Kowalczyk, Smoroń and Kopacz (2019), surface runoff is the largest "carrier" of material eroded from the surface of arable fields. In the case of OP, the point of statistically significant change was in May 2022, after the completion of renovation works (Fig. 4). This means that with the commencement of modernisation works, the content of P was much higher than the content of OP, which could indicate the release of P from bottom sediments.

During the renovation of the weir, the water flow in the river and the availability of sunlight in the water changed, which could have had a significant impact on the change in the physico-chemical parameters of the water. Analysing the available literature on weirs, it should be noted that, in general, there is no information on the impact of weir upgrades on the nutrient content of rivers and even less on river and lake systems. Mostly, the subject of weirs is related to work on changes in the retention, of water resources in the area. There are several works in the literature on water quality in the context of damming weirs (Włodarczyk, 2006; Seo, Lee and Kim, 2019; Nowak *et al.*, 2022), but these works do not deal with analysis related to changes resulting from modernisation works. According to the literature, maintenance works, such as modernisation or reconstruction of the weir, may negatively affect the ecological condition of the river, in particular the ecological condition of river and lake systems (due to their specificity) (Prus, Pawlaczyk and Popek, 2017). However, there is a gap in the scientific literature regarding the topic of renovation of weirs on rivers and river-lake systems, along with a description of the impact on the river quality. There is a lot of information available about the construction of weirs on rivers and their importance for water quality. However, the issue of weir renovation is particularly important in the case of lowland rivers. By the applicable rules, weir repair works should be carried out in strictly defined conditions to avoid an ecological disaster. Prus, Popek and Pawlaczyk (2018) report that, in the case of lowland rivers with a fine-grained substrate, the renovation or maintenance of the weir may change the ecological status, and may significantly affect the change in physico-chemical parameters. In accordance with good practices in river maintenance, the rules should be followed when renovating weirs. These actions are rated as "usually minimally invasive", but only under certain conditions. In the case of lowland rivers with a sandy substrate, it is recommended that such treatments be performed after July 15, due to the possibility of increasing the content of P and OP in the

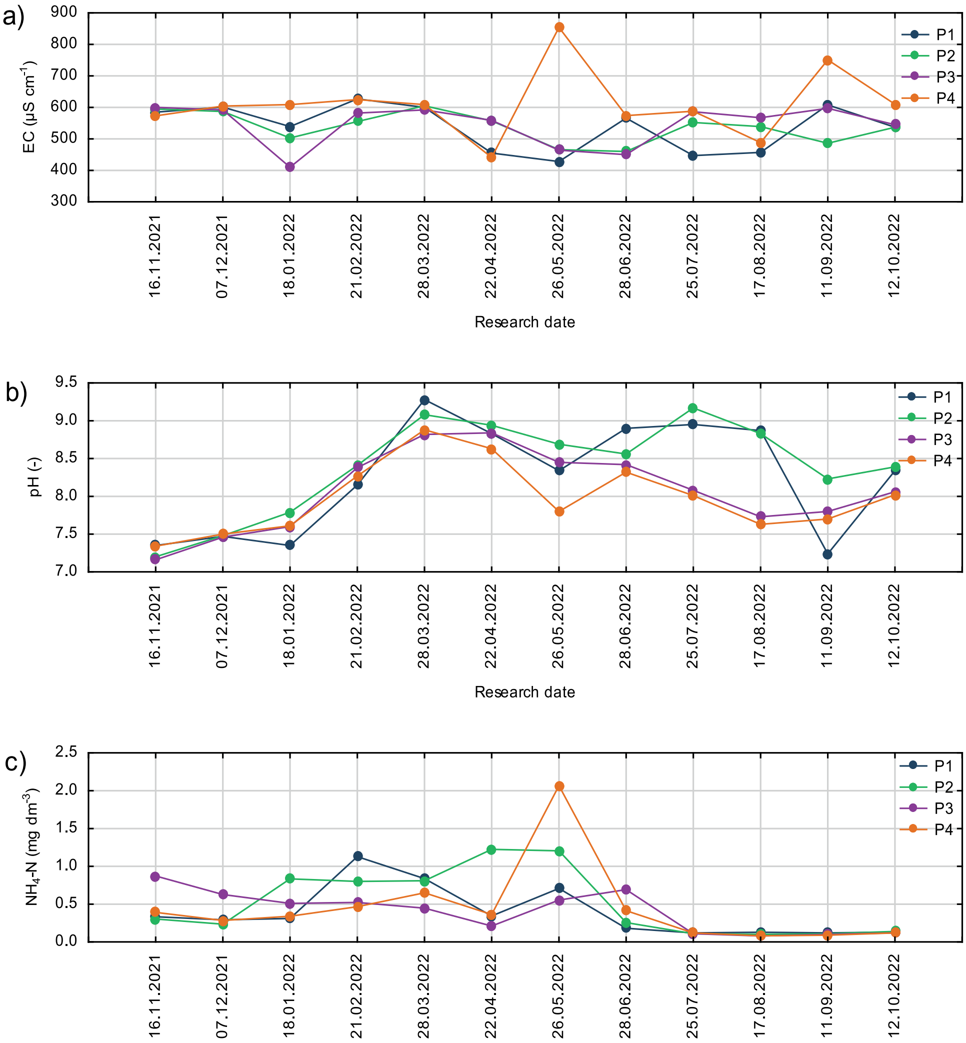

Fig. 3. Temporal variability of water in the hydrological year 2022: a) *EC*, b) pH, c) NH_4-N; P1–P4 as in Fig. 1; source: own study

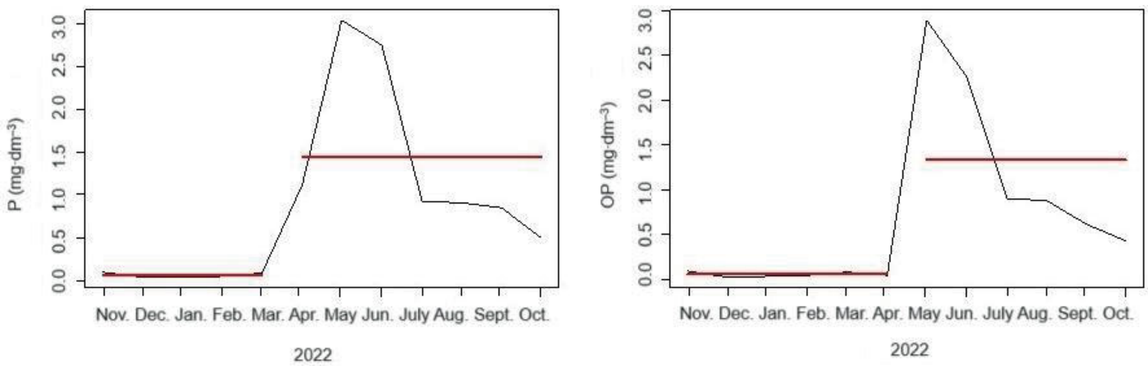

Fig. 4. The content of OP and P in water in the hydrological year 2022, with the statistical change point; source: own study

river. The research area is an area dominated by sandy soil formations, which, as a result of renovation works, could have increased the content of P and OP in the water of the Głuszynka River. Additionally, the period in which the work was carried out was characterised by high air temperatures, which translated into high water temperatures. As part of the fieldwork, the water temperature was measured on site and averaged 17.2°C in May, which could hurt changes in physico-chemical parameters. Perhaps choosing a different date for the weir renovation (after July 15, as indicated in Prus, Popek and Pawlaczyk (2018)) would limit the increase of P and OP in the water. Unfortunately, the changes in the content of P and OP were significant in this case. Similar results were obtained by Cha *et al.* (2013), who analysed the variability of physico-chemical parameters in the Yeongsan River, before and after the construction of the weir. Parameters such as BOD_5, COD, P, and N were analysed. Among the analysed parameters, in the case of P and N, significant changes were noted during the construction of the weir, and after completion of construction, a slight improvement was noted for these parameters. In turn, Lee, Park and Cheon (2018), examining the variability of the parameters of the Nakdong River in Korea, noted a decrease in the content of P and chlorophyll in the period after the renovation of the weir, in the middle and lower sections of the river.

This study also analysed the further period after the modernisation works. The content of P and OP decreased significantly in the following months, but their values were still several times higher than the values of these parameters before the renovation. Unfortunately, the statistical analysis showed that the renovation of the weir below Lake Jeziory Wielkie contributed to a significant deterioration of water quality in the river-lake system. Due to the nature of this system, this had a serious impact on reservoirs further downstream. The average content of total phosphorus at point P4 in the post-modernisation period was 18 times higher than the average content of this element before the conservation works. Similarly, in the case of OP, their content was 17 times higher.

CONCLUSIONS

The presented research showed that the renovation works carried out on the weir located on the Głuszynka River significantly affected the content of of orthophosphate(V) (OP). Analysis of water quality before and after weir renovation showed that after the modernisation works the parameters are characterised by several times higher P and OP content compared to the period before the weir renovation. The statistical change point analysis identified statistically significant change for the parameters, such as P and OP. Significant changes in P were observed before the start of the renovation work, while in the case of OP, the point of statistically significant change was a water sample taken in May 2022, i.e. just after the renovation work had been completed. It is recommended that future modernisation works be carried out during periods of lower ecological risk. Following the completion of the construction project, consistent and vigilant monitoring of the water's condition and its effects on the ecological landscape is imperative.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at https://www.jwld.pl/files/Supplementary_material_Janicka.pdf

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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