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ASSESSMENT OF RESTORED WATER BODIES IN A RIVER-LAKE SYSTEM BASED ON PHOSPHORUS CONCENTRATIONS

OCENA FUNKCJONOWANIA ZRENATURYZOWANYCH ZBIORNIKÓW WODNYCH NALEŻĄCYCH DO SYSTEMU RZECZNO-JEZIORNEGO NA PODSTAWIE STĘŻEŃ FOSFORU

Abstract: Three water bodies restored around 30 years ago were studied: Lake Nowe Wloki, Lake Setalskie Duze and Lake Setalskie Male, connected by the Setal Stream into a single river-lake system in the Olsztyn Lakeland, approximately 25 km north of the city of Olsztyn, in the District of Dywity.

The objective of this study was to evaluate the functioning of three water bodies in a river-lake system restored around 30 years ago. Particular attention was paid to water quality and the trophic status of the analyzed lakes, assessed based on seasonal changes in phosphorus concentrations.

A river-lake system comprising restored water bodies in rural areas reduces the concentrations of biogens migrating from the catchment area, thus minimizing the effects of potential eutrophication in larger rivers and other water bodies to which the system's watercourses evacuate. As regards lake inflows, a drop in total phosphorus levels was noted after passage through the water body, and high concentrations of total P resulted from the polymictic character of the studied lakes.

The inflows to water bodies that form a chain system supply substantial amounts of total P to the lakes, leading to the retention of excessive phosphorus concentrations and speeding up processes which deteriorate water quality and lake functioning. Over a three-year experimental period, the average concentrations of phosphorus, – an element limiting primary production – varied from 0.22 to 0.34 mg $P_{total} \cdot dm^{-3}$ in the water bodies within the studied river-lake system. The absence of water stratification (hypolimnion) contributed to intensive phosphorus recirculation and very high trophy levels in the examined lakes. According to Nurnberg, the total phosphorus concentrations determined in the spring are indicative of their hypetrophy.

Keywords: river-lake system, polymictic lakes, primary production, hypertrophy

The migration and inflow of eutrophicating elements into water bodies from local sources is affected by natural and anthropogenic factors. Natural factors account for

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weather, land relief and inclination, the properties of soil and biogenic substances. Anthropogenic factors include the type of land use and the manner of farm estate management [1, 2].

Phosphorus, nitrogen and potassium form the "chemical trio" of nutrients which are highly demanded by plants [3]. Ecosystems deficient in phosphorus (oligotrophic) are characterized by low biomass production and high biodiversity. Phosphorus is readily absorbed and blocked in the ecosystem, therefore, it reaches water bodies in smallest quantities, and it is also most readily removed from water systems. The phosphorus content of water bodies is usually minimal, and this feature is used in measures aiming to restrict eutrophication. Excessive phosphorus levels in aquatic ecosystems increase water fertility and they are the main cause of eutrophication. The anthropogenic sources of water-borne and soil-borne phosphorus include fertilizers, wastewater and detergents [4].

Young glacial areas feature specific systems of hydrographic objects [5, 6]. Watercourses are connected with lakes, and they are referred to as river-lake systems. Water bodies are interconnected via sections of river water gaps (often intermittent watercourses), creating a cohesive drainage network. River sections linking lakes are short, and most of them are overflows. To a smaller extent and along smaller sections, they are supplied by underground streams, and excess water overflows from one water body to another [7]. The resulting ecosystem seasonally retains matter migrating from the catchment. The circulation of biophilic elements is a factor that contributes to water trophy [8, 9]. As part of a single river-lake system, a lake can therefore both trap and evacuate phosphorus [10, 11]. Research studies investigating agricultural catchment areas indicate that anthropogenic factors significantly contribute to the eutrophication of restored water bodies.

The objective of this study was to evaluate water bodies in a river-lake system restored around 30 years ago. Particular attention was paid to water quality and the trophic status of the analyzed lakes, assessed based on seasonal changes in phosphorus concentrations.

Materials and methods

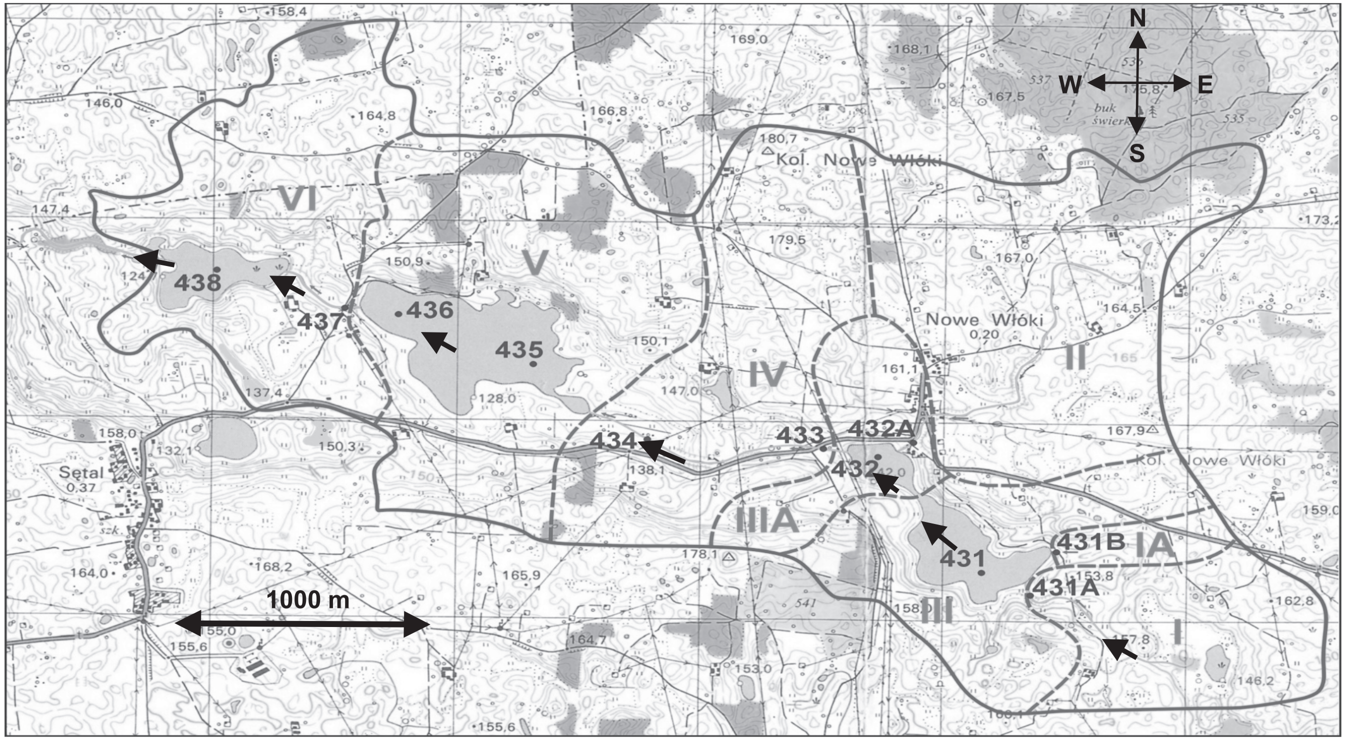
The study investigated three water bodies in the Protected Landscape Area in the Valley of Middle River Lyna, comprising Lake Nowe Wloki, Lake Setalskie Duze and Lake Setalskie Male, connected by the Setal Stream to form a single, cohesive river-lake system. The studied objects were drained in the 19th century during a comprehensive land improvement project to create agricultural grassland. In view of the need for small retention reservoirs and fire water reservoirs in rural areas, the discussed water bodies were restored at the turn of the 1970s and the 1980s. The lakes are situated along the Setalski drainage canal (presently referred to as the Setal Stream), and the restoration involved a water damming project on the Stream. The studied water bodies are polymictic lakes with a small average depth of 1.1 to 2.3 m.

Lake Nowe Wloki is situated near the village of Nowe Wloki, and the remaining water bodies, Lake Setalskie Duze and Lake Setalski Male, are found in the village of

Setal, Dywity District in the Olsztyn Lakeland, approximately 25 km north of the city of Olsztyn. The analyzed district is weakly afforested, it comprises mostly agricultural land with the predominance of brown soils. The local soils are cohesive, and they have developed mostly from heavy loamy sand underlain by a layer of light loam throughout the entire soil profile [Central Statistical Office 2003].

The analyzed catchment has a total surface area of 883.82 ha. It was initially divided into eight subcatchments which were assigned the following numbers: I, IA, II, III, IIIA, IV, V, VI. The location of each subcatchment and measuring points is presented in Fig. 1.

Lake Nowe Wloki comprises two sections: the southern section which is the main lake basin (point 431) and the northern bay (point 432) with a combined area of 19.67 ha. The main lake basin has an elongated profile, and it is adjacent to farmland on the right bank and meadows on the left bank. The northern bay has a much smaller area, and it is found in the vicinity of a road leading to Setal. In the north, the lake directly neighbors three farming estates without livestock. Both meander pools are connected by a characteristic contraction densely overgrown with sedge (*Carex* sp.) and common reed (*Phragmites australis* (Cav) Trin. Ex Steudel). The lake's catchment has a combined area of 408.19 ha, and it comprises smaller subcatchments. Catchment I features the upper course of the Setal Stream which reaches the lake, marked as number 431A. This subcatchment is occupied by arable land and grasslands in 89 %. Drainage canal 431B runs in the eastern part of the lake (main basin), and it evacuates water from subcatchment IA into the lake. This subcatchment has the inclination of 6.6 %, and 94 % of its area is occupied by farmland. The area was drained in September 2006. In the north, the lake neighbors the village of Nowe Wloki which does not operate a sewer system. This part of the lake constitutes subcatchment II which feeds into Lake Nowe Wloki (northern bay) via drainage ditch 432A. Subcatchment III constitutes the lake's direct catchment. Water is evacuated from the lake (433) via a watercourse marked by point 434 (in subcatchment IV) which feeds into Lake Setalskie Duze. Lake Setalskie Duze (its eastern section was assigned number 435, the western section – 436) is the largest of the studied objects with an area of 41.34 ha. It is situated in (direct) catchment V which is occupied by farmland in more than 54 %. The northern part of the catchment features three land plots with holiday cottages made of brick. The land plots enclose three fish ponds and two small farms, one of which raises 20 cows. Cattle are grazed on pastures on the north-eastern side of the lake. The eastern part of the lake has a small bay with a depth of 1.4 m and a gently sloping bottom. It is densely overgrown with common reed (*Phragmites australis* (Cav) Trin. Ex Steudel), reed canarygrass (*Phalaris arundinacea* L.), sedge (*Carex* sp.) and simplestem bur-reed (*Sparganium erectum* L.). Water is evacuated from the water body via a ditch (437), and it is carried by a drainage canal along farm fields to Lake Setalskie Male. Similarly to Lake Nowe Wloki, the stream supplying and evacuating water from the lake is also a seasonal watercourse (stagnant water) which is affected by weather conditions. Lake Setalskie Male is separated from Lake Setalskie Duze by a (straight line) distance of approximately 300 m, and it is situated at the lowest altitude (124.7 m above sea level). The lake has an area of 8.07 ha, and it is found in direct catchment VI. The northern section of the



Key: ● – sampling and measuring points; – the investigated water bodies; I, II – subcatchment numbers; – subcatchment boundaries; – catchment boundary; – direction of water flow.

Fig. 1. Location of the studied water bodies and measuring points, scale 1:25 000
Location and description of measuring points: 431A – inflow to the main basin of Lake Nowe Wloki (Setal Stream), 431B – drainage canal inflowing to Lake Nowe Wloki, 432A – drainage ditch inflowing to Lake Nowe Wloki, 431 – main basin of Lake Nowe Wloki, 432 – northern bay of Lake Nowe Wloki, 433 – outflow from Lake Nowe Wloki, 434 – inflow to Lake Setalskie Duze, 435 – eastern part of Lake Setalskie Duze, 436 – western part of Setalskie Duze 437 – outflow from Lake Setalskie Duze and inflow to Lake Setalskie Male, 438 – Lake Setalskie Male

catchment is steeply inclined in the direction of the water body, and the southern part is a gently undulating area. The lake's banks feature no trees, and they are overgrown only with common reed (*Phragmites australis* (Cav) Trin. Ex Steudel). The lake has an inflow (connecting it to Lake Setalskie Duze) and an outflow which evacuates water all the way to the Lyna River (the outflow was not studied due to limited access).

During the three-year period of the experiment, the following crops were grown in the agricultural catchment of Lake Nowe Wloki: triticale in 2005, winter barley in 2006, rapeseed in 2007. The following crop regime was observed in the catchment of Lake Setalskie Duze: rapeseed in 2005, triticale in 2006 and rye in 2007. Arable land in the catchment of Lake Setalskie Male had the following crop structure: rapeseed in 2005, fallowing in 2006, rapeseed in 2007.

Water samples for laboratory analyses were collected once a month over a period of three years (2005–2007). Total phosphorus and inorganic phosphorus concentrations were determined in the samples. The analyses were performed by the standard method proposed by Hermanowicz et al [12]. The species composition of the described vegetation was determined on the site according to Rutkowski's classification key [13]. An analysis of variance and the determination of statistical differences between datasets were performed with the use of Duncan's test in the Statistica 7 application. The remaining results, including mean, minimum and maximum values, standard deviation, median and the coefficient of variation, were processed statistically using the EXCEL application.

Results and discussion

The trophic status of a water body is largely determined by its phosphorus content. In lake ecosystems, total phosphorus and inorganic phosphorus concentrations are subject to significant seasonal variation. In addition to the phosphorus load supplied from the catchment, phosphorus levels increase due to various internal mechanisms which are intensified with a rise in the lake's trophic state index. A drop in phosphorus concentrations is observed when the element is accumulated in bottom deposits and organisms, in particular macrophyte tissues [14].

Total phosphorus concentrations in the studied chain system lakes were marked by significant variations in successive hydrological years. The average concentrations noted throughout the entire experimental period were similar (except in the northern bay of Lake Nowe Wloki, point 431), reaching 0.22 to 0.34 mg $P_{total} \cdot dm^{-3}$, with significant variations in the course of the examined three-year period (0.03 to 2.27 mg $P_{total} \cdot dm^{-3}$). The median concentrations in the analyzed water bodies were determined in the range of 0.16 to 0.25 mg $P_{total} \cdot dm^{-3}$ (Table 1).

As regards inflow waters supplying Lake Nowe Wloki, significantly lower average total P concentrations were noted over the three-year period in field stream 431A (Stream) at 0.17 mg $P_{total} \cdot dm^{-3}$, which is indicative of water purity class I [15]. In waters evacuated from fields via the drainage canal (431B) and waters evacuated from the agricultural catchment with farm estates via the drainage ditch (432A), the average total P concentrations were more than 60 % higher, reaching 0.29 mg $P_{total} \cdot dm^{-3}$, which

Table 1

Annual and seasonal variations in total P concentrations in the studied water bodies in hydrological years 2005–2007 [mg · dm^{-3}]
A two-way analysis of variance (*Two-Way Anova p ≤ 0.001*) was performed using Duncan's test

Site			Measuring point	2005	2006	2007	2005–2007					Seasonal average (over 3 years)			
				average			average	fluctuations	±SD	CV	median	winter	spring	summer	fall
Flow-through water bodies															
Lake Nowe Wloki	Inflows	Setal Stream	431A*	0.18^{a}	0.12^{a}	0.21^{a}	**0.17**^{a}	0.06–0.52	0.14	80	0.16	0.15^{ab}	0.19^{ab}	0.18^{ab}	0.22^{ab}
		drainage canal	431B	X	0.11^{a}	0.28^{a}	**0.29**^{ab}	0.04–0.84	0.23	115	0.19	0.36^{ab}	0.11^{a}	0.43^{ab}	0.18^{ab}
		drainage ditch	432A	0.23^{a}	0.31^{a}	0.33^{a}	**0.29**^{ab}	0.05–0.75	0.20	70	0.21	0.18^{ab}	0.17^{ab}	0.55^{b}	0.35^{ab}
	main basin		431	0.20^{a}	0.24^{a}	0.31^{a}	**0.25**^{ab}	0.04–0.78	0.21	84	0.20	0.17^{ab}	0.14^{a}	0.35^{ab}	0.36^{ab}
	northern bay		432	0.24^{a}	0.41^{b}	0.35^{a}	**0.34**^{b}	0.04–2.27	0.38	112	0.25	0.27^{ab}	0.41^{ab}	0.35^{ab}	0.31^{ab}
	outflow		433	0.31^{a}	0.25^{a}	0.27^{a}	**0.28**^{ab}	0.05–0.86	0.18	67	0.23	0.19^{ab}	0.17^{ab}	0.46^{ab}	0.28^{ab}
Lake Setalskie Duze	inflow		434	0.25^{a}	0.19^{a}	0.34^{a}	**0.26**^{ab}	0.04–1.08	0.20	77	0.20	0.20^{ab}	0.17^{ab}	0.43^{ab}	0.23^{ab}
	eastern part		435	0.19^{a}	0.23^{a}	0.24^{a}	**0.22**^{ab}	0.03–0.48	0.13	60	0.18	0.10^{a}	0.17^{ab}	0.37^{ab}	0.25^{ab}
	western part		436	0.17^{a}	0.23^{a}	0.31^{a}	**0.24**^{ab}	0.06–0.97	0.17	71	0.21	0.22^{ab}	0.18^{ab}	0.30^{ab}	0.25^{ab}
	outflow		437	0.16^{a}	0.22^{a}	0.34^{a}	**0.22**^{ab}	0.03–0.62	0.13	59	0.20	0.19^{ab}	0.16^{ab}	0.29^{ab}	0.25^{ab}
Lake Setalskie Male			438	0.16^{a}	0.23^{a}	0.27^{a}	**0.22**^{ab}	0.06–0.56	0.14	62	0.16	0.17^{ab}	0.27^{ab}	0.23^{ab}	0.18^{ab}

Key: X – the catchment was drained in 2006.
431A – inflow to the main basin of Lake Nowe Wloki (Setal Stream), 431B – drainage canal inflowing to Lake Nowe Wloki (14-month average), 432A – drainage ditch inflowing to the northern bay of Lake Nowe Wloki, 431 – main basin of Lake Nowe Wloki, 432 – northern bay of Lake Nowe Wloki, 433 – outflow from Lake Nowe Wloki, 434 – inflow to Lake Setalskie Duze, 435 – eastern part of Lake Setalskie Duze, 436 – western part of Setalskie Duze 437 – outflow from Lake Setalskie

corresponds to water purity class III, ie water of satisfactory quality (more than half of the analyzed samples were within the above range). The highest median concentrations were determined for drainage ditch 432A at 0.21 mg $P_{total} \cdot dm^{-3}$ (Table 1). Clear differences in total P concentrations were reported between the main (southern) meander pool and the northern meander pool in Lake Nowe Wloki. In the analyzed period, the average levels of total P reached 0.25 mg $P_{total} \cdot dm^{-3}$ in the main lake basin (431), and they were lower by more than 30 % (statistically non-significant) in comparison with the northern bay (432). The bay was characterized by the highest variation of 112 % with fluctuations in the range of 0.04–2.27 mg $P_{total} \cdot dm^{-3}$, and its average concentrations of total P reached 0.34 mg$P_{total} \cdot dm^{-3}$. Extreme concentrations of total P (2.27 mg $P_{total} \cdot dm^{-3}$) and N-NH_4 were reported in March 2006 when the lake remained under ice cover, creating a supportive environment for the release of phosphorus from deposits into the water. In general, high average concentrations of total P in the northern bay of Lake Nowe Wloki could point to the allochthonous origins of phosphorus, mostly surface runoffs from developed areas [16]. Water bodies situated at lower altitudes often receive matter and pollutants from extensive catchment areas of river tributaries, and they are subjected to the adverse effects of anthropogenic pressure [8, 17], as demonstrated by high total P levels in the drainage ditch (Table 1). In the outflow from Lake Nowe Wloki (point 433) and the inflow to Lake Setalskie Duze (point 434), the average total P concentrations were higher than in the bay, reaching 0.28 mg $P_{total} \cdot dm^{-3}$ and 0.26 mg $P_{total} \cdot dm^{-3}$, respectively. The above resulted mainly from phytosorption, as demonstrated by much lower total P levels in the spring (Table 1). In the eastern part of Lake Setalskie Duze (point 435), the average total P concentrations were somewhat lower (by approximately 8 %) in comparison with the western part (point 436) throughout the entire experiment. The above was largely due to heavy rainfall in 2007. According to Kajak [14], torrential rain may lead to the rapid runoff of substantial quantities of the annual nutrient load. The above theory is supported by high phosphorus concentrations noted in January (0.965 mg $P_{total} \cdot dm^{-3}$), June (0.395 mg $P_{total} \cdot dm^{-3}$) and July (0.415 mg $P_{total} \cdot dm^{-3}$) which were marked by heavy precipitation reaching 122 mm, 116 mm and 122 mm, respectively. In this part of the water body, the catchment features steeper slopes which probably contributed to a more intense supply of ground-borne phosphorus from the direct catchment occupied by holiday cottages. In the eastern section (435), the banks are overgrown with aquatic vegetation as well as shrubs and trees that inhibit runoffs from the catchment. In the outflow (437) from Lake Setalskie Duze, the average phosphorus concentrations were maintained at the level noted in the lake throughout the period of the study, implying that outflow waters were of purity class III. In Lake Setalskie Male, the average total P concentrations (0.22 mg $P_{total} \cdot dm^{-3}$) were identical to those reported in the eastern part of Lake Setalskie Duze, but the median concentration (0.16 mg $P_{total} \cdot dm^{-3}$) was lowest among the studied water bodies (Table 1).

The group of lakes situated along the river was characterized by an increase in total phosphorus concentrations in the summer (Table 1). Lower oxygen levels noted in the summer supported the release of phosphorus and its transfer to the water. As demonstrated by various authors [18–20], total phosphorus levels increase with a drop in the water table which decreases the volume of the water body, increases nutrient concentrations and restricts the dilution of biogenic elements. The above phenomenon often lowers water quality and increases total phosphorus concentrations, an indicator of the lake's trophic status. Summer variations in the phosphorus content of water also result from a rise in COD (Chemical Qxygen Demand) levels during that season (46.1–50.1 mg $O_2 \cdot dm^{-3}$).

In the group of flow-through water bodies, the lowest total P concentrations were observed in Lake Setalskie Male in the summer. The lake's surface is overgrown with vegetation in 20 % which limits wave motion and inhibits phosphorus release from the sediments. Phosphorus was additionally consumed by lush vegetation covering the lake bottom, mostly frogbit (*Hydrocharis morsus-ranae* L.) and spiked water milfoil (*Myriophyllum spicatum* L.) (Table 1).

In general, total phosphorus concentrations reached the highest values in all water bodies in the wet year 2007. High precipitation totals (822 mm) supported the leaching of phosphorus from the soil. In comparison with 2006, the atmospheric deposition of phosphorus was twice higher in 2007 (1.84 kg $\cdot$ $ha^{-1} \cdot yr^{-1}$), providing an additional source of total phosphorus [21]. The variations in dissolved phosphorus levels were similar to the changes noted in total phosphorus concentrations.

In the studied water bodies, the average inorganic phosphorus concentrations determined throughout the experimental period ranged from 0.03 mg $P\text{-}PO_4 \cdot dm^{-3}$ to 0.06 mg $P\text{-}PO_4 \cdot dm^{-3}$ in the northern bay (431) of Lake Nowe Wloki where the highest variations in $P\text{-}PO_4$ levels were also noted in the range of 0.003 to 1.07 mg $P\text{-}PO_4 \cdot dm^{-3}$ (Table 2).

In gauging sections in the subcatchments of Lake Nowe Wloki, drainage ditch 432A (0.15 mg $P\text{-}PO_4 \cdot dm^{-3}$) was marked by significantly higher average concentrations of inorganic phosphorus which had a 52 % share of total phosphorus (Table 2, Fig. 2). The above resulted from high $P\text{-}PO_4$ levels in the summer and fall (no phytosorption of phosphorus activated in the mineralization process towards the end of and after the growing season). The average $P\text{-}PO_4$ levels reported during the three-year period in watercourse 431A and drainage canal 431B were identical at 0.04 mg $P\text{-}PO_4 \cdot dm^{-3}$, but in 431A (Stream), the share of inorganic phosphorus in total P was 10 % higher in comparison with drainage canal 431B. In all lakes connected by the Setal Stream, considerably higher average concentrations of $P\text{-}PO_4$ were determined in the northern bay (432) of Lake Nowe Wloki at 0.06 mg $P\text{-}PO_4 \cdot dm^{-3}$. In those water bodies, $P\text{-}PO_4$ had a significantly smaller share of total phosphorus concentrations in comparison with flowing waters, at 12 to 18 %. The studied lakes' outflows were marked by considerable variations in the average levels of inorganic phosphorus. In the outflow (433) from Lake Nowe Wloki, the average $P\text{-}PO_4$ concentrations throughout the period of this experiment were significantly higher than in the outflow (437) from Lake Setalskie Duze. Higher levels of $P\text{-}PO_4$ (which had a 32 % share of total phosphorus) resulted from the mobilization of the studied element from organic matter accumulated in deposits (a broad, shallow and densely overgrown ditch), as demonstrated by its high concentrations in the summer at 0.20 mg $P\text{-}PO_4 \cdot dm^{-3}$ (Table 2, Fig. 2).

Table 2

Annual and seasonal variations in P-PO_4 concentrations in the studied water bodies in hydrological years 2005–2007 [mg · dm^{-3}]
A two-way analysis of variance (*Two-Way Anova* $p \leq 0.001$) was performed using Duncan's test

P-PO_4																
Site			Measuring point	2005	2006	2007	2005–2007					Seasonal average (over 3 years)			
				average			average	fluctuations	±SD	CV	median	winter	spring	summer	fall
Flow-through water bodies															
Lake Nowe Wloki	Inflows	Setal Stream	431A*	0.04^{a}	0.05^{a}	0.05^{a}	**0.04^{a}**	0.014–0.19	0.04	94	0.03	0.06^{a}	0.04^{a}	0.06^{a}	0.03^{a}
		drainage canal	431B	—	0.04^{a}	0.04^{a}	**$\underline{0.04}^{a}$**	0.023–0.07	0.01	33	0.04	0.04^{a}	0.03^{a}	0.06^{a}	0.04^{a}
		drainage ditch	432A	0.09^{a}	0.26^{b}	0.10^{a}	**0.15^{c}**	0.020–0.35	0.11	75	0.08	0.05^{a}	0.10^{ab}	0.25^{c}	0.14^{abc}
	main basin			0.03^{a}	0.04^{a}	0.03^{a}	**0.03^{a}**	0.002–0.08	0.02	52	0.03	0.02^{a}	0.04^{a}	0.04^{a}	0.04^{a}
	northern bay		432	0.04^{a}	0.12^{a}	0.02^{a}	**0.06^{ab}**	0.003–1.07	0.18	293	0.03	0.03^{a}	0.14^{abc}	0.04^{a}	0.03^{a}
	outflow		433	0.14^{a}	0.10^{a}	0.04^{a}	**0.09^{b}**	0.001–0.46	0.10	117	0.04	0.04^{a}	0.03^{a}	0.20^{bc}	0.08^{ab}
Lake Setalskie Duze	inflow		434	0.04^{a}	0.06^{a}	0.03^{a}	**0.04^{a}**	0.010–0.14	0.03	67	0.03	0.04^{a}	0.03^{a}	0.05^{a}	0.05^{a}
	eastern part		435	0.04^{a}	0.04^{a}	0.02^{a}	**0.03^{a}**	0.003–0.08	0.02	63	0.03	0.02^{a}	0.03^{a}	0.04^{a}	0.04^{a}
	western part		436	0.04^{a}	0.04^{a}	0.03^{a}	**0.03^{a}**	0.006–0.06	0.02	47	0.03	0.03^{a}	0.04^{a}	0.04^{a}	0.04^{a}
	outflow		437	0.04^{a}	0.05^{a}	0.03^{a}	**0.04^{a}**	0.004–0.14	0.02	53	0.03	0.04^{a}	0.03^{a}	0.04^{a}	0.04^{a}
Lake Setalskie Male			438	0.02^{a}	0.04^{a}	0.02^{a}	**0.03^{a}**	0.004–0.27	0.04	159	0.02	0.03^{a}	0.03^{a}	0.02^{a}	0.02^{a}

Key: refer to Table 1.

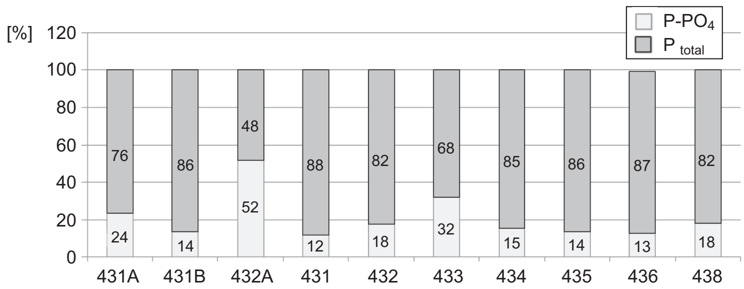


Fig. 2. Percentage share of P-PO_4 in P concentrations in the river-lake system
431A – inflow to the main basin of Lake Nowe Wloki (Setal Stream), 431B – drainage canal inflowing to Lake Nowe Wloki (14-month average), 432A – drainage ditch inflowing to the northern bay of Lake Nowe Wloki, 431 – main basin of Lake Nowe Wloki, 432 – northern bay of Lake Nowe Wloki, 433 – outflow from Lake Nowe Wloki, 434 – inflow to Lake Setalskie Duze, 435 – eastern part of Lake Setalskie Duze, 436 – western part of Setalskie Duze 437 – outflow from Lake Setalskie Duze and inflow to Lake Setalskie Male, 438 – Lake Setalskie Male

According to prior experiments investigating the role of river-lake systems [9, 11, 23], biogenic substances migrating with water in the form of mineral compounds and suspensions are readily captured and retained by ecosystems of the type which also produce substantial amounts of organic matter. The variations in total P concentrations in a chain system, expressed by differences in the studied element's percentage content, are shown in Fig. 3. Total phosphorus concentrations in the upper section of the Stream which feeds into the main basin of Lake Nowe Wloki and opens the studied system represent 100 %. The noted results (Fig. 3) indicate that areas where river and lake waters mix [22] play an important role in a chain system where lakes are intersected by river sections and other watercourses (Fig. 3). The average total phosphorus values in inflows (drainage canal 431B, drainage ditch 432A, river section between two lakes – 434) were higher, and they decreased after passage through the lake. A significant increase in total phosphorus concentrations (from 129 % to 165 %) was observed along the course of the Setal Stream. It was particularly high in the outflow from the northern bay (433) of Lake Nowe Wloki (65 % higher than in the upper section of the stream – 431A) which receives water via the drainage ditch from the village with no sewer system. The noted increase was clearly affected by the dry year 2006 when the water body had limited supply. In the peak of the growing season of 2006, which was marked by a drought, higher hydrological stability and reduced water flow, the water body exported phosphorus accumulated in deposits under layers of oxygen-deficient water, as shown by very high average concentrations of total phosphorus (Table 1, Fig. 3). Despite the noted increase in phosphorus levels in the Stream, the results of this study indicate that in view of total P levels in all inflows to the lakes, the analyzed water bodies act as thresholds in the transport process where phosphorus is accumulated in deposits, as shown by total phosphorus concentrations of 129 % in Lake Setalskie Male (Fig. 3).

In reference to the studied lakes' unquestioned role of biogeochemical barriers, the results of this experiment show that despite the negative processes observed in the

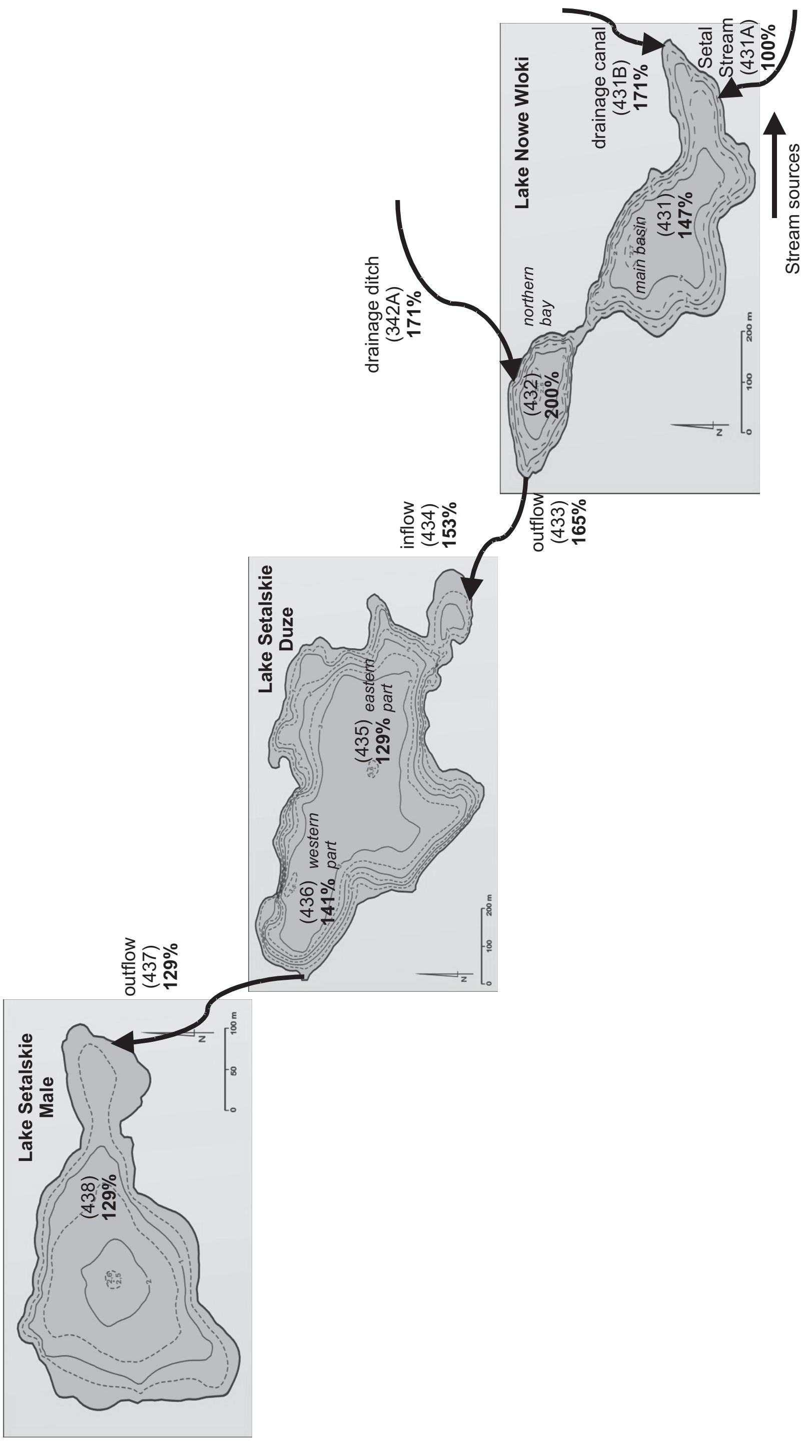


Fig. 3. The effect of the restored water bodies on phosphorus concentrations in the river-lake system in rural areas (phosphorus concentrations in the source section of the watercourse represent 100 %)

analyzed water bodies, chain systems minimize the potential consequences of eutrophication in large rivers and other water bodies to which the system's waters evacuate.

As regards variations in phosphorus concentrations, it has been noted that in shallow lakes with a high share of active bottom area, bottom deposits come into frequent contact with surface water, supporting the release of phosphorus accumulated at the bottom of the lake [9, 14, 24]. As shown by the study investigating seasonal variations in the analyzed element's concentrations, the above process is most intense in the summer, and the levels of released P may actually exceed external supply. Similar conclusions were formulated by Provini and Premazzi [25]. The absence of water stratification (hypolimnion) contributed to intensive phosphorus recirculation and very low trophy levels [26]. Throughout the three-year period of the experiment, the average concentrations of phosphorus, an element limiting primary production, in the restored water bodies were within the range reported for lakes in agricultural regions [27]. According to Nurnberg [28], total phosphorus concentrations determined in the spring are indicative of their hypetrophy (Table 3). Similar results were reported by Kawara et al [29], Szyperek [30] and Skwierawski [31] who argued that shallow water bodies are at an immense risk of eutrophication due to their contribution to reducing the concentrations of biogenic elements supplied from the catchment. Research studies investigating water trophy demonstrate that in addition to the eutrophication of polymictic water bodies situated in agricultural catchments, a serious risk is also posed by rural settlements without sewer systems which are the main source of biogenic substances responsible for high trophy levels [16, 32–35].

Table 3

Assessment of trophic status of the studied water bodies based on the spring concentrations of total P in view of Nurnberg criteria [1996]

Water body	Spring concentrations of total P							
	2005		2006		2007		Average for 2005–2007	
	Index	Trophic status	Index	Trophic status	Index	Trophic status	Index	Trophic status
Lake Nowe Wloki								
431 (main basin)	0.12	H	0.14	H	0.15	H	0.14	H
432 (northern bay)	0.12	H	0.84	H	0.28	H	0.41	H
Lake Setalskie Duze (average for 435, 436)	0.10	E	0.25	H	0.17	H	0.17	H
Lake Setalskie Male 438	0.22	H	0.26	H	0.29	H	0.27	H

E – eutrophic; H – hypertrophic.

While analyzing the trophic status of water bodies, the N:P ratio has to be determined to indicate which of the two biogenic elements stimulates algal growth [36, 37]. The N:P ratio calculated in this study (Table 4) indicates that phosphorus did not inhibit the development of algae in the analyzed flow-through water bodies [21]. In view of the above, primary production could have been determined mainly by the presence of nitrogen [8, 38]. The only exception was the largest water body (Lake Setalskie Duze) where primary production levels were affected by both nitrogen and phosphorus.

Table 4

Total nitrogen to total phosphorus ratio in the studied water bodies according to [Criteria... 2003]

Ratio	Water body			
	Lake Nowe Wloki (main basin)	Lake Nowe Wloki (northern bay)	Lake Setalskie Duze (average for 435, 436)	Lake Setalskie Male
N:P	9.2	8.1	10.7	9.1

Conclusions

1. The river-lake system comprising restored lakes on the Setal Stream reduces the concentrations of phosphorus migrating from the catchment areas, thus minimizing the effects of potential eutrophication in larger rivers and other water bodies to which the system's watercourses evacuate.

2. As regards lake inflows, a drop in total phosphorus levels was noted after passage through the water bodies, and high concentrations of total phosphorus (especially in the summer) resulted from the polymictic character of the studied lakes where nutrients are released from interstitial waters.

3. The relatively high average spring concentrations of total phosphorus noted over the three-year period of the experiment (0.14–0.41 mg $P_{total} \cdot dm^{-3}$) were determined at the hypertrophy level, pointing to the extreme eutrophication of the restored lakes.

4. The pollutants supplied by a drainage ditch from rural settlements with no sewer system had a clearly negative effect on water quality in the studied system. The highest P_{total} and $P\text{-}PO_4$ concentrations were noted in the northern bay of Lake Nowe Wloki.

5. A rapid increase in the trophic levels of the lakes restored along the Setal Stream could lead to the accumulation of deposits and the gradual shallowing of the lakes, thus preventing those water bodies from fulfilling their initial functions.

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OCENA FUNKCJONOWANIA ZRENATURYZOWANYCH ZBIORNIKÓW WODNYCH NALEŻĄCYCH DO SYSTEMU RZECZNO-JEZIORNEGO NA PODSTAWIE STĘŻEŃ FOSFORU

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Abstrakt: Badaniami objęto trzy zbiorniki wodne odtworzone przed około 30 laty: jezioro Nowe Włóki, jezioro Setalskie Duże i jezioro Setalskie Małe, połączone Strugą Setal w jeden system rzeczno-jeziorny, położone na Pojezierzu Olsztyńskim około 25 km na północ od Olsztyna w gminie Dywity.

Celem pracy była ocena funkcjonowania odtworzonych przed około 30 laty zbiorników wodnych, należących do systemu rzeczno-jeziornego, ze szczególnym uwzględnienie jakości wody i stanu troficznego jezior na podstawie stężeń fosforu i jego sezonowych zmian.

Istnienie systemu rzeczno-jeziornego, dzięki odtworzonym zbiornikom na terenach wiejskich pozwala na redukcję stężeń (kumulacji związków biogennych) migrujących ze zlewni, zmniejszając w ten sposób skutki potencjalnej eutrofizacji większych rzek i innych akwenów, do których cieki systemu uchodzą.

W przypadku wód dopływających do jezior zaobserwowano poprawę w zakresie obniżenia stężeń fosforu ogólnego, po ich przepłynięcie przez akweny, a utrzymywanie się dużych koncentracji P_{og} w wodach badanych jezior należy wiązać także z ich polimiktycznym charakterem.

Z dostawy zanieczyszczeń (P_{og}) do zbiorników układu paciorkowego wynika, iż wody dopływów wnoszą do jezior znaczne jego ilości, powodując ponadnormatywne stężenia P_{og} w wodzie akwenów i przyspieszając w ten sposób procesy, które pogarszają jej jakość oraz funkcjonowanie jezior. Stwierdzono, że w wodzie odtworzonych zbiorników średnie z trzech lat stężenia fosforu – pierwiastka limitującego produkcję pierwotną, mieściły się w zakresie od 0,22 do 0,34 mg $P_{og} \cdot dm^{-3}$. Brak stratyfikacji wód (hypolimnionu), wpłynął na intensywną recyrkulację fosforu i bardzo wysoką trofię wód. Według Nurnberga wiosenne koncentracje P_{og}, wskazują na stan ich skrajnego przeżyźnienia czyli hipertrofii.

Słowa kluczowe: system rzeczno-jeziorny, jeziora polimiktyczne, produkcja pierwotna, hipertrofia