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The significance of oxbow lakes for the ecosystem of afforested river valleys

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Abstract: The interest in significance of forest areas in water quality improvement has been increasing since creation of biogeochemical barriers became effective tools against the input of pollutants to surface water from diffuse sources. Along meandering river valleys, numerous floodplain lakes often appear as valuable water ecosystems but of advanced eutrophy. Their trophic status depends not only on the hydrological connectivity with the river but also land use in the direct vicinity of the reservoir. Research on water ecosystems in the postglacial river valleys in northern Poland contributed to identification of the role of woodland area in pollutants migration in the valley of the Łyna River.

The study on the ecosystem concerned seasonal variation in nutrient concentrations (N and P) and bottom sediments properties in relation to hydrological conditions (water level fluctuations). Based on the collected data we attempted prediction of the reservoir lifetime. Depending on hydrological, geological and topographic conditions the origin of water supply of the basin is changing. Annual water level fluctuations in the range of 200 cm cause the basin capacity variation as much as 5 times. Nevertheless, water quality in the lake was conditioned by the riverine supply, the significant share in the lake feeding has groundwater supply from hillslope aquifer and seepage through alluvial aquifer. Contribution of every origin supply depends on river flow rate and valley water level, it depends on alluvial ground formations permeability and relief. Hillslope erosion of the concave bank was responsible for high nitrogen and phosphorus outflows. The research showed that primary and secondary production and freshets contributed to intensive deposition of bottom sediments in oxbow lake. The increase rate of sediment determined on the base of matter balance was 10 times higher than deposition rate of bottom sediments in glacial lakes. The accelerated processes of silting-up and shallowing and terrestialization of the valuable ecosystems indicate the necessity of floodpain lakes protection due to ecological functions they play in forestry landscape.

Key words: *bottom sediments, forest retention, nitrogen, oxbow lakes, phosphorus, water protection, water retention*

INTRODUCTION

Recent years have witnessed growing environmental pollution caused by anthropogenic activity. It is manifested not only by higher fertility of water ecosystems, where the symptoms of a trophic imbalance are relatively easy to observe, but also of forest ecosystems (ZERBE, 2002). The main contributors to this process are pollutant emissions to water, soil and ambient air. Whereas the function of large water bodies has been largely recognized, the role of smaller aquatic ecosystems, such as oxbow lakes which are part of the so called small water cycle, remained undervalued for a long time. Individual water bodies may have a relatively minor effect on the environment, yet they are important microcatchments which collectively determine the water balance of a given area. Oxbow lakes are a characteristic feature of lowland river valleys. They are formed by the rivers' natural propensity to meander in the middle of their course, and by complex hydrodynamic processes. This instability of river channels creates oxbow lakes stretching on both banks of the river's present course in the form of elongated, arching water bodies. In afforested river valleys, oxbow lakes are a source of water for forest habitats, and they play an important role in view of the progressing scarcity of water supplies observed in the past two decades (PIERZGALSKI and TYSZKA, 2000). In addition to their hydrological and microclimatic role of retention reservoirs, oxbow lakes also have a number of vital functions in river valley ecosystems. Their biocenotic significance has been long recognized. Together with rivers and hydrological catchments, oxbow lakes form a unique ecosystem which contributes to the natural diversity of those areas. They are the habitat of many populous water fauna species which inhabit sites with highly diverse moisture content. Oxbow lakes offer a highly supportive environment for the growth of water and hygrophilous flora – an abundant source of biomass which underlines the food pyramid for the ecosystem. Riparian forests in the direct proximity of oxbow lakes are also sites of great natural value. Riparian forests were encountered in all valleys of Central Europe before man started to reclaim and use those areas for farming purposes. Today, they are a unique natural feature. Oxbow lakes play a sozological function by accumulating water-borne biogenic elements and organic substances. Organic components are thus deposited from the water cycle in the ecosystem and are permanently fixed in bottom deposits (GLIŃSKA-LEWCZUK and KOBUS, 2005a; 2005b). Oxbow lakes greatly contribute to the region's scenic and recreational value, enhancing its tourist appeal. Water bodies may have complementary roles, but they may also be mutually exclusive. They vary subject to size, location and the quality of accumulated water. Regardless of the above considerations, oxbow lakes always increase the availability of water resources, improve water balance and determine water course flow.

There are very few published studies investigating the effect of the agricultural use of river valleys on the degradation of oxbow lakes. The manner in which the feed areas of oxbow lakes are used can profoundly affect the type of transformations observed in those areas, which can lead to permanent changes. This issue has been addressed very superficially in the existing studies, and references to oxbow lakes were made only when describing the hydrological and geomorphological properties of rivers (LEOPOLD and WOLMAN, 1960; CALLANDER, 1978; DĘBSKI, 1978; KLIMASZEWSKI, 1978). The scant publications focus mostly on water and rush vegetation in oxbow lake habitats (TOMASZEWICZ, 1969; PIÓRECKI, 1980; WOJTASZEK, 1989). Very few studies discuss the role of oxbow lakes as biogeochemical barriers against pollutants migrating from river catchments (HALICKI and SZUSTAKOWSKI, 2003; GLIŃSKA-LEWCZUK, 2005; PIŃSKWAR and JEZIERSKA-MADZIAR, 2005; KOBUS and GLIŃSKA-LEWCZUK, 2006).

The objective of this study was to analyze the effects of differences in agricultural and forested land use on the quality of the water resources accumulated in oxbow lakes as well as to determine the accumulation capacity of oxbow lakes and to investigate the need and the possibilities for protecting those water bodies.

MATERIALS AND METHODS

The experiment was conducted in the valley of the middle course of the Łyna River. The river meanders significantly in this section, forming numerous oxbow lakes. The highest number of oxbow lakes of different age and at various stages of transformation, can be found between Dobre Miasto and Lidzbark Warmiński. Since the last glaciation period, the formation and disappearance of oxbow lakes was a dynamic process, as shown by numerous depressions in the channel of the Łyna River. The river's natural activity was modified by man – as a result, numerous relatively young oxbow lakes were formed during channel regulation works in the mid 1970s.

Site characteristics. The experiment covered two oxbow lakes (Fig. 1) situated between Dobre Miasto and Wichrowo (around 40 km north of Olsztyn). Those water bodies are at an early stage of evolutionary development – they were formed during river regulation works (straightening of the river channel). The first site is an oxbow lake in the vicinity of the village of Smolajny, situated on the left bank of the Łyna River, in an agricultural area. The valley has a width of around 1.5 km at this point. The edge zone of the valley and its slope are occupied by arable land, while the bottom of the valley in the direct vicinity of the water body is covered by reclaimed grassland. Arable lands, sown with oat and rye, were fertilized with a dose of 60 $kg \cdot ha^{-1}$ of NPK. Livestock was about 0.5 $LU \cdot ha^{-1}$. Due to a gentle slope towards the oxbow lake, may be responsible for the receiving by the water body a certain amount of fertilizers which are not used in the crop production. It seems to be main threat to the ecosystem health as the nutrient excess causes the loss of ecological equilibrium.

Along this section, the river erodes the bank in the littoral zone and transports large quantities of fine-grained deposits. Moraine remnants are abundant in the valley. Stagnant deposits (PIAŚCIK, 1986) with the granulometric composition of silty clay and clay are found in larger meanders in the area of Smolajny. Peat bogs occur

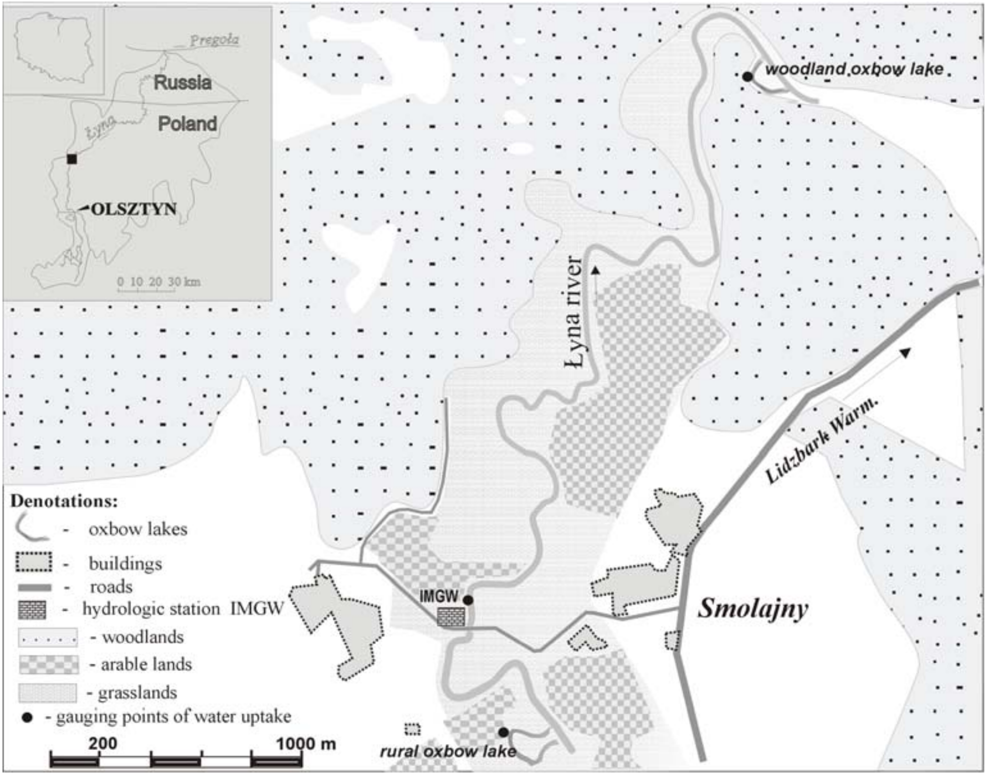

Fig. 1. Location of experimental sites

sporadically in the investigated area, most of them are formed by stagnant deposits which retained ground water runoffs from higher plains. They comprise peat-muck soils of alder wood peat on the plateau margin, separated from the river channel by humus-rich alluvial soil. To a depth of 1 m, peat is strongly decomposed and its structure is fractured. It is underlain by moderately decomposed rush peat. The peat forming process was replaced by the silting process, leading to the formation of a 35 cm thick layer of mineral and organic deposits. Below there is an organic layer of strongly decomposed alder wood peat. The analyzed soils are used as meadows. A narrow strip between the above formations and very heavy humus-rich alluvial soils by the river are occupied by a thin layer of heavy alluvial soils on alder wood peat. The surface layers comprise silty loam, and the deeper layers – silty clay. Bog iron-ores occur frequently. Owing to gley and sod formation, the investigated soils are abundant in humus, in particular in the surface layer. Very heavy, deep humus-rich alluvial soils are found between the high plain and medium-deep humus-rich alluvial soils. Their surface is made of alluvial deposits to a depth of 1.5 m, resting on fine-grained slightly loamy sand. The second oxbow lake is found in the vicinity of the village of Wichrowo, around 6 km down the river on its right bank, in the

Wichrowo Forest Division. The river valley is narrow (around 300 m) with many gaps, which is why the oxbow lake is set very closely, almost parallel, to the river bed. The left bank comprises end-moraine formations which slope steeply in the direction of the river valley, reaching a relative height of 50 m. The deposits feature mostly silty loam on heavy loam and clay, and in the alluvial layer of the valley – heavy loamy sand and clay. Due to the proximity of moraine formations, clay layers interbedded with stones and gravels are found locally at the bottom of the river bed.

On the right side of the valley, the concave bank of the woodland oxbow lake is shielded by a sand escarpment, several meters in height, composed of loose and slightly loamy sand. The water body is surrounded by pine trees plantations (*Pinus silvestris*) at the average age of 50 years. The Łyna River intersects an outwash plain belt from the north-west to the south-east. On the side of the concave bank, a low strip of alluvial soils is covered with sedge and grass. The oxbow lake was formed during channel regulation works commissioned by the Regional Board for Agricultural Investments in Olsztyn in 1982. Oxbow lakes have a stable water table and are connected to the river via a fork on the side of the lower water level, which is consistent with the principles of natural river regulation.

The experimental period covered hydrological years 2004–2005. The hydrological features of the investigated water bodies were determined during water stage observations at the Institute of Meteorology and Water Management station in Smolajny to monitor retention capacity and changes in water quality. Morphometric measurements were performed at sections spaced every 40 m perpendicular to the axis of the oxbow lake. Depth measurements were carried out every 2 m in each section with the use of a Single Beam Humminbird 100 SX sonar. The results were used to compile bathymetric charts of the analyzed oxbow lakes.

During field experiments, water from oxbow lakes and the Łyna River (Fig. 1) was sampled for physical and chemical analyses. Samples were taken 1 m beneath water surface every month and more frequently during periods of high water supply from the catchment. At the sampling site, the samples were analyzed to determine: electrolytic conductivity (using a WTW Hanna HI 8733 portable conductometer), pH, temperature (ºC), dissolved oxygen concentration ($mg \cdot dm^{-3}$), percentage of oxygen saturation (%) using a pH/oxygen/Redox Multiline P3 probe. Nitrogen and phosphorus levels were determined by universally accepted methods (HERMANOWICZ *et al*., 1999) in the laboratory of the Department of Land Improvement and Environmental Management. Nitrate, nitrite nitrogen and phosphorus levels were determined using colorimetric methods. Ammonium nitrogen – Nessler method and total nitrogen – Kiejdahl method. Bottom deposits were sampled to determine the effect that water alimentation to oxbow lakes and the river had on the sedimentation process. Samples were collected from the central part of the analyzed water bodies at the deepest points, from the upper and lower forks near the river connection point. An Eijkelkamp Beeker – type core probe with a diameter of 6 cm was used to collect samples with intact structure. Cores were divided morphologically into 3 layers with a thickness of 0.05 m to 0.60 m. An average sample from each layer was subjected to chemical analyses. The physical properties of fresh samples were determined by the Troels-Smith method (TOBOLSKI, 2000), including dry residue, bulk density, pH, organic matter, organic carbon, nitrogen and phosphorus content.

RESULTS AND DISCUSSION

Since oxbow lakes are connected to the river, the water resource dynamics and morphometric parameters vary subject to fluctuations in the water table (Fig. 2). Intensified water supply from the alimentation zone increases the surface area of oxbow lakes up to the point when water spills out into the valley. As a result, the area is completely flooded and the river occupies the entire valley. Oxbow lakes are connected to the Łyna River and their basins change dynamically due to fluctuations in the river's water table which exceeded 200 m in the investigated period. The presented bathygraphic and capacity curves illustrate the shape of oxbow lake basins. Flattened curve sections correspond to a high water stage which was observed in each monitored water body during floods in the experimental period. The location of the woodland oxbow lake in a narrow valley affected the course of the surface curve. When feed water reaches the turning point on the left bank, the oxbow lake can expand further only in this direction.

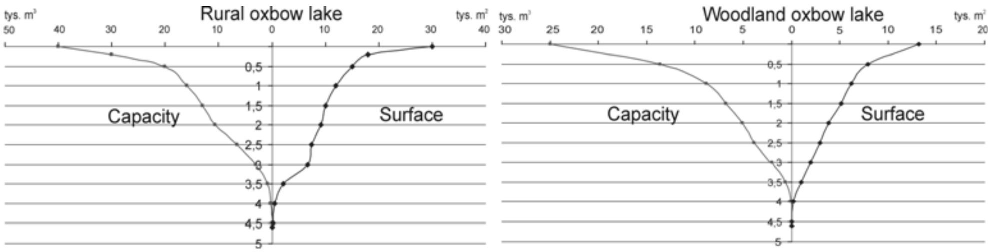

Fig. 2. Capacity and surface curves of the analyzed oxbow lakes

The quantity and type of nutrients found in water bodies are a measure of the quality of aquatic ecosystems. The characteristic features of oxbow lakes are shaped by both natural attributes as well as the manner in which their waters and catchments are used. Selected physical and chemical properties of the investigated water bodies are presented in Table 1.

All water samples had a neutral pH. Electrolytic conductivity was characteristic of natural surface water. Dissolved ion concentrations were most stable in river water (*SD* ± 39 $\mu S \cdot cm^{-1}$).

Table 1. Mean and standard deviation of physical and chemical parameters in the analyzed oxbow lakes

Parameter	Unit	River		Woodland oxbow lake		Rural oxbow lake	
		mean	±*SD*	mean	±*SD*	mean	±*SD*
pH	pH	7.78	0.42	7.61	0.39	7.51	0.37
EC	$\mu S \cdot cm^{-1}$	412	39	420	84	449	103
$N\text{-}NO_2$	$mg \cdot dm^{-3}$	0.015	0.006	0.013	0.014	0.011	0.012
$N\text{-}NO_3$	$mg \cdot dm^{-3}$	0.53	0.31	0.32	0.36	0.30	0.31
$N\text{-}NH_4$	$mg \cdot dm^{-3}$	0.37	0.55	0.43	0.53	0.30	0.45
TN	$mg \cdot dm^{-3}$	2.73	1.02	2.76	0.59	2.48	0.98
$P\text{-}PO_4$	$mg \cdot dm^{-3}$	0.14	0.08	0.15	0.09	0.09	0.06
TP	$mg \cdot dm^{-3}$	0.40	0.35	0.43	0.22	0.34	0.27

Nitrite nitrogen is a transitory form in the cycle of nitrogen transformations between ammonium and nitrate forms, or vice versa, subject to the prevalent oxygen conditions. The lowest nitrite nitrogen concentrations were determined in the rural oxbow lake. The water of oxbow lakes had a much higher capacity for biological uptake of nitrates than river water. The presence of ammonia in water is usually due to the biochemical decomposition of organic plant and animal nitrogen compounds, mostly proteins, or nitrate reduction in polluted water. The highest average concentrations were noted in the woodland oxbow lake (0.43 $mg \cdot dm^{-3}$). The highest average level of total nitrogen in this water body (2.76 $mg \cdot dm^{-3}$) validates the theory that ammonium nitrogen originates from the decomposition of organic matter. Since phosphorus is believed to play the key role in the eutrophication of water bodies, its presence is an important indicator of water quality (KOC and SKWIERAWSKI, 2004; GLIŃSKA-LEWCZUK, 2009). The highest $P\text{-}PO_4$ concentrations were reported in the woodland oxbow lake (average of 0.15 $mg \cdot dm^{-3}$). Relatively high levels were noted in river water (0.14 $mg \cdot dm^{-3}$). In the group of investigated water bodies, the woodland oxbow lake had also the highest concentrations of total phosphorus (0.43 $mg \cdot dm^{-3}$).

Seasonal variability is one of the factors determining the quality of water in the investigated ecosystems. Changes occurring in a water environment are determined by different factors, and season is one of the most important considerations (Fig. 3). In surface water, nitrite nitrogen is rapidly transformed into oxidized or reduced forms, subject to oxidoreduction conditions. Nitrite nitrogen was marked by the lowest concentrations and by the highest stability in oxbow lakes in the summer season (around 0.003 $mg \cdot dm^{-3}$).

Concentrations of $N\text{-}NO_2$ were statistically higher ($P > 0.05$) in the water of the Łyna River in the spring and summer than in other types of water bodies. The highest interquartile range, especially in the autumn (0.004–0.032 $mg \cdot dm^{-3}$), was reported in the woodland oxbow lake, pointing to high fluctuations in nitrite nitrogen levels. $N\text{-}NO_2$ concentrations were stable in river water during periods of lim-

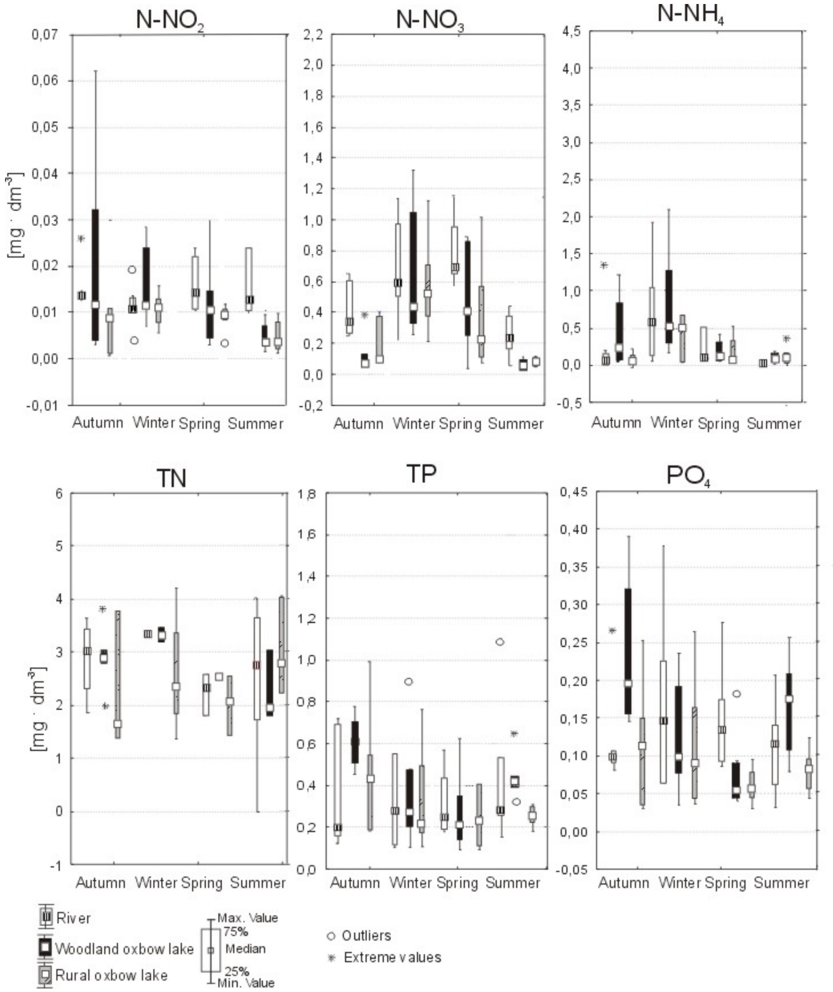

Fig. 3. Seasonal variability in nitrogen and phosphorus concentrations in the analyzed oxbow lakes

ited biological change. Nitrate nitrogen levels in the river were generally statistically significant higher than those observed in oxbow lakes, indicating that those ecosystems are highly capable of purifying their waters by phytosorption. A high level of biological sorption in the summer and autumn was responsible for nitrate fixation, mostly by hydrophilic vegetation. A high interquartile range of $N\text{-}NO_2$ concentrations and high fluctuations in surface water were observed in the non-growing season.

During this period, significantly higher $N\text{-}NO_3$ levels were stated in the water of the woodland oxbow lake than of the rural oxbow lake. It should be noted, however, that in the growing season, most of the values observed in the woodland oxbow lake approximated the median (nearly 0.1 $mg \cdot dm^{-3}$). This could be attributed to a more stable oxygen environment during the summer and autumn low water stage.

Ammonium nitrogen concentrations were more stable than other nitrogen forms in various seasons of the year, as confirmed by relatively lower interquartile ranges of variation. The statistically significant higher levels of the compound were reported only in the winter, in particular in the woodland oxbow lake. In addition to biological desorption, an increase in $N\text{-}NH_4$ concentrations could also be due to the anaerobic conditions under the ice cover where this form of nitrogen from the decomposition of accumulated plant substances and deposits is not oxidized. An increase in ammonium nitrogen concentrations resulting from the decomposition of organic matter in the post-growing season takes place at a faster rate in the woodland oxbow lake than in the rural oxbow lake. Greater drops in night temperatures are usually reported in the autumn. The woodland oxbow lake is shielded by an afforested scarp on the side of the concave shore and the prevalent light conditions are much less favorable than in the rural oxbow lake. In the summer, light rays reach this water body only in the late afternoon. Even on sunny autumn days, water in the woodland oxbow lake can never be sufficiently heated to compensate for the night temperature drops. Lower insolation and unfavorable thermal conditions restrict assimilation, reduce biomass accumulation, thus inhibiting vegetation and causing water plants to die out. An earlier initiation of those processes in the woodland oxbow lake could accelerate the decomposition of vegetation whose life cycle is governed by climatic variability and the release of nitrogen from decomposing matter. This assumption is validated by relatively, statistically significant high concentrations of total nitrogen in the woodland oxbow lake in the autumn. Nitrogen concentrations in this oxbow lake were also significantly higher than in other water bodies in the spring and winter, and were marked by high stability (all values approximated the median). Phosphate levels in the river were significantly higher than in the remaining water bodies in the spring (median of around 0.14 $mg \cdot dm^{-3}$) and winter (median of around 0.15 $mg \cdot dm^{-3}$). In the summer and autumn, mineral phosphorus concentrations in the woodland oxbow lake exceeded the levels determined in other water bodies (median of around 0.18 $mg \cdot dm^{-3}$ in the summer and around 0.20 $mg \cdot dm^{-3}$ in the autumn) due to the intrasystem cycling of water at low water stages. Higher interquartile ranges and concentration medians were noted in the rural oxbow lake in the spring and autumn. Similarly to other nutrients, high concentrations of total phosphorus were noted in the woodland oxbow lake in the autumn (median of 0.6 $mg \cdot dm^{-3}$). In the summer, those concentrations were also the highest (median of 0.4 $mg \cdot dm^{-3}$) and more stable in this water body. During warm periods, phosphorus is released in the process of mineralization of organic matter which is accumulated in the lake from falling leaves and wood detritus. Intensified denudation with surface runoff at times of high precipitation causes phosphorus to migrate with soil particles down the sparsely overgrown escarpment on the shore. P concentrations were statistically higher in both oxbow lakes in the non-growing season when compared to growing season. The above validates the contemporary views on phosphorus migration to surface water. This nutrient is generally associated with soil material, which is why surface runoffs play a much greater role in supplying surface water bodies with phosphorus than infiltration (HALICKI and SZUSTAKOWSKI, 2003). It is probable, in an environment of light acidic forest soils, phosphorus supplied by precipitation migrates to water more easily than in rural areas where soils are more abundant in the sorption complex. For this reason, water bodies in afforested areas with sandy soils may have an inhibiting effect on the flow (and runoff) of phosphorus to rivers and lakes by fixing this nutrient in plants and deposits.

Although the water quality class of the river and oxbow lakes is similar and belong to the class IV based on all studied parameters listed in the Rozporządzenie… (2004), the differences are distinct when their seasonal variability is analysed (Fig. 3). Due to limited exchange of water between the studied oxbow lakes and the Łyna River, the influence of the river water on the concentrations of nutrients shows minor significance.

The sedimentation process responsible for the formation of bottom deposits is probably the most important contributor to the disappearance of shallow water bodies from river floodplains (TARELA *et al.*, 1999; MIRANDA *et al.*, 2001). Sedimentation physically reduces the depth of water bodies and limits their storage capacity. The supplied suspension is often an abundant source of organic matter and nutrients from the catchment area, which initiate a new primary production process leading to the eutrophication of water bodies. In the investigated oxbow lakes, the sedimentation process takes place under different conditions than in larger post-glacial lakes. In oxbow lakes, sedimentation is generated mainly by river floodplains and the distribution of autochthonous vegetation. When the high water stage reaches the inundation terrace, it floods all river bed hollows in the vicinity. The rate of water flow determines the type of processes taking place in oxbow lakes. The nutrient balance is negative if water flows at a rate faster than that which supports sedimentation. Deposits may be evacuated from the lake with flood waters, and this process "rejuvenates" water bodies. If the flow rate supports sedimentation of allochthonous matter from the river bed and its catchment, the nutrient balance in oxbow lakes is positive and the supplied suspension fills the lake basin. During low stage periods, the river's contact with oxbow lakes is limited to the lower fork, and the sedimentation process involves mostly autochthonous nutrients of non-mineralized plant debris characteristic of the littoral zone of deeper lakes. The thickness of bottom deposits in the investigated oxbow lakes, which were formed in relatively lentic ecosystems after the lake had been cut off from the river bed, varied subject to sedimentation conditions and corresponded to the isolated top strata of the collected samples (Tab. 2). In lakes with steep, even precipitous banks, the process of deposit formation was largely determined by denudation. For this reason, the thickness of deposits formed after the access to oxbow lakes had been

Table 2. Physical and chemical properties of bottom deposit layers in the analyzed oxbow lakes

Parameter Unit	Stratification of oxbow lake bottom sediments					
	surface layer (superstratum)		interlayer		sublayer	
	rural oxbow lake	wood-land ox-bow lake	rural oxbow lake	wood-land ox-bow lake	rural oxbow lake	wood-land ox-bow lake
Dry matter, %	38.3	43.2	76.5	66.9	79.8	86.8
Density, $g \cdot cm^{-3}$	1.44	1.26	1.71	1.71	2.06	2.19
pH_{KCl}	7.38	7.09	7.69	7.56	7.73	7.70
Organic matter, % DM	24.3	31.2	2.02	13.7	1.25	0.90
Organic carbon, % DM	14.1	18.5	1.17	7.95	0.73	0.50
Nitrogen, $g \cdot kg^{-1}$ DM	10.5	8.01	0.68	6.74	0.40	0.57
$N\text{-}NO_3$, $mg \cdot kg^{-1}$ DM	1.42	0.95	5.82	5.05	1.01	0.92
$N\text{-}NH_4$, $mg \cdot kg^{-1}$ DM	78.2	98.4	20.2	21.5	4.11	4.61
Phosphorus, $g \cdot kg^{-1}$ DM	2.39	2.72	0.62	0.96	0.64	0.71
Available phosphorus, $g \cdot kg^{-1}$ DM	0.08	0.13	0.11	0.15	0.10	0.12

blocked reached up to 40 cm. In shallower forks, where the euphotic zone extends to the bottom and offers a more supportive environment for vegetation growth, deposit thickness reached around 20–25 cm. In lower forks connected with the river, organic matter from the river bed had a higher share of the accumulated deposits whose thickness reached around 30 cm. The elongated shape of oxbow lakes obstructs the flow of organic matter in the direction of the deepest parts of the lake. Deep waters do not support the growth of macrophytes which play a vital role in supplying deposits with autochthonous organic matter. Due to the above, the thinnest layer of deposits, with a thickness of 15–20 cm, was accumulated in the deepest parts of oxbow lakes. The average thickness of deposits accumulated after the lakes had been cut off from the river bed was approximately 30 cm for all studied water bodies.

The density of bottom deposits in the analyzed water bodies increased with sediment depth due to the pressure exerted by the overlying layers (Tab. 2). The highest accumulation of organic matter was observed in the surface layers of the sampled cores which were deposited in stagnant water. A clear drop in organic matter content was noted in successive, underlying layers. Organic matter concentrations decrease with depth mainly due to the supply of autochthonous matter: surface strata have a biogenic origin and are mineralized with time. Fine- and medium-grained sand layers are supplied with rock debris before oxbow lakes are cut off from the river.

Higher wood detritus (Dl) content was observed in the deposits of the woodland oxbow lake. The content of carbon, as the main building block of organic matter, was strongly determined by the content of organic substances. The highest carbon concentrations were determined in the top stratum of deposits in the woodland oxbow lake (18.5% DM), and the lowest – in the bottom stratum (0.50% DM). The distribution of nitrogen was similar to that of organic matter and organic carbon, and the highest nitrogen concentrations were reported in the top stratum of the lake's deposits what explains its organic and autochtonic origin. Greater vertical variations (26-fold) and higher concentrations in the surface layer (10.5 $g \cdot kg^{-1}$ DM) were observed in the rural oxbow lake. Nitrogen levels were also high (6.74 $g \cdot kg^{-1}$ DM) in the central part of the woodland oxbow lake. Due to the release of $N\text{-}NO_3$ from deposit surface to interstitial water, the transfer of nitrate nitrogen down the profile and the accumulation of $N\text{-}NO_3$ by rooted plants, the highest nitrogen concentrations were noted in the center of the sampled cores. A steady decrease in $N\text{-}NH_4$ levels was observed in successive strata. Higher concentrations were observed in the surface deposits of the woodland oxbow lake (98.4 $mg \cdot kg^{-1}$ DM). The accumulation of phosphorus in the bottom deposits of water bodies blocks the circulation of this nutrient in water ecosystems (SOBCZYŃSKI and SIEPAK, 2001). Maximum phosphorus concentrations in the bottom deposits of oxbow lakes were found in the surface strata of the deposits. Higher levels were noted in the woodland oxbow lake, reaching 4 g $P \cdot kg^{-1}$ in its deepest parts. Available phosphorus was more evenly distributed. The highest labile phosphorus levels were reported in the central strata and its concentrations were higher in the woodland oxbow lake (0.15 $g \cdot kg^{-1}$ DM), thus offering a supportive environment for the growth of rooted nympheids. The C : N : P weight ratio in the top stratum of bottom deposits of the rural oxbow lake was 59 : 4.4 : 1, while in the woodland lake, the investigated biogenic elements occurred at a ratio of 68 : 2.9 : 1. According to KAJAK (2001), low nitrogen concentrations are characteristic of allochthonous matter reaching water bodies, producing a C : N ratio of 20–50 : 1. Higher nitrogen levels in oxbow lakes are, therefore, indicative of the high share of autochthonous matter in bottom deposits.

SUMMARY

During a high river stage, the water and terrestrial habitats within the reach of the river valley are flooded. The expansion of the flood water route is accompanied by the elongation of the wetted perimeter in the cross-sectional area of the valley. Water flow resistance increases, and it is additionally reinforced by the roughness of the vegetation cover at the bottom of the valley. Open oxbow lakes formed by meandering channels (rather than multi-channel rivers) on straight and wet alluvia are flooded together with the meander island. A general decrease in flow rate leads to the sedimentation of suspension particles carried by water. The sedimentation of easily deposited matter particles is the main process taking place in oxbow lakes during river floods. The above explains the relatively fast accumulation of allochthonous deposits in water bodies of this type (CULLUM *et al.*, 2006). This process

supports evolutionary changes leading to a gradual shallowing and extinction of oxbow lakes. Only a very high water stage is capable of unlocking deposits from the bottom of oxbow lakes. Flood waters rinse the lake basin, purifying its waters and removing excess sediments. The cumulative character of water bodies in the vicinity of river floodplains can, however, contribute to the purification of river waters through the sedimentation of suspensions and biological sorption of the dissolved nutrients. The balance between those two processes is determined by various natural factors, and it may be easily upset by human activity which speeds up the eutrophication and degradation of water bodies. The average thickness of deposits in all investigated oxbow lakes after they had been cut off from the river channel was approximately 30 cm. Since the studied lakes had been formed during regulatory works on the Łyna River which ended in 1982, annual sedimentation was estimated at 13 mm. The average sedimentation rate in moderately fertile lakes approximates 1 mm per year (MIKULSKI, 1982), which clearly indicates that the rate of eutrophication of these oxbow lakes is very high.

The functioning of the investigated water bodies may be determined by their existing interconnections and openness to hydrochemical and biological exchange with other environments. The highest concentrations of biogenic substances were observed in the woodland oxbow lake. At the same time, the chemical composition of its water was more similar to the parameters of river water. Both lakes have a similar type of connection with the river channel, i.e. the connection is activated when water levels in the channel and the cross-sectional area at the point of connection are similar. For this reason, surface water exchange is very similar in both water bodies. The chemical affinity of the woodland lake's water and channel water could be attributed to the lake's direct proximity to the river channel. The lake is adjacent to the channel, and the capillary suction of channel water and alluvial water largely determines the quality of lake waters.

The quality of the water ecosystem of oxbow lakes is determined by various natural factors, but it is also largely shaped by human activity. The rural oxbow lake has an arching shape and a higher shoreline development index, which are characteristic features of water bodies of natural origin. Due to the above, the ecotonal zone is longer at the contact point of water and terrestrial ecosystems. The rural oxbow lake is directly surrounded by grasslands which play the role of a biogeochemical barrier against biogenes evacuated from arable land situated at higher altitudes. The water properties of the woodland oxbow lake are determined by different geomorphological conditions and a different type of land use. Biogenic elements are fed into the lake with surface runoffs from the steep valley scarp and are also supplied by decomposed organic matter from leaves and trees which became uprooted when water eroded the concave shore of this river section. Due to the above, higher concentrations of organic matter, nitrogen and phosphorus were determined in the woodland oxbow lake.

Like all ecosystems, oxbow lakes in the valley of the Łyna River require a comprehensive protection scheme covering the water body, its direct catchment as well as its indirect catchment and the entire river valley. The soil and water protection functions of forests are largely determined by the species composition of local communities, as well as by the topographic, soil and moisture conditions of a given area. Riparian forests are the natural cover of river valleys, but they are not encountered in the middle course of the Łyna River. Most areas in the investigated valley are overgrown with pine trees which are used for industrial purposes. The quality of water in the woodland oxbow lake could be improved by antierosive planting trees (as *Salix fragilis*, *Salix xrubens*, *Alnus glutinosa*, *Fraxinus exc.*, *Prunus padus etc.*) and shrub species (*Cornus sp.*, *Sambucus nigra*, *Rosa canina*, *Corylus avellana*, *Vibumum opulus*, *Cataegus* etc.) compatible with the local habitat and permanently stabilizing the area by laying a continuous cover of grass sod to prevent the valley scarp from eroding.

CONCLUSIONS

1. Water-borne nutrients are supplied to oxbow lakes by different means. Their concentrations vary over time and are directly determined by the river's flow volume, water stage in the valley, permeability of alluvial deposits and local relief features.

2. Most of the parameters determining the quality of water and bottom deposits reached the highest values in the woodland oxbow lake where biogenes could be fed with surface runoffs from the steep valley scarp and could be additionally supplied by decomposed organic matter from leaves and trees which became uprooted when water eroded the concave shore of this river section. Due to the above, higher concentrations of organic matter, nitrogen and phosphorus were determined in the woodland oxbow lake.

3. Bottom deposits in oxbow lakes were formed mainly in the process of primary and secondary production as well as during periods of high water stage in the river, as indicated by the presence of autochthonous and allochthonous fractions from the river channel in the analyzed deposits. The sedimentation process in the investigated lakes took place at least 10-times faster than in glacial lakes.

4. Oxbow lakes are highly susceptible to degradation due to natural phenomena occurring during water exchange and the lakes' morphometric properties. Those processes have an adverse effect on the water environment. Oxbow lakes are very fragile ecosystems requiring adequate protection measures that guarantee their survival in the landscape of the Łyna River valley.

5. A protection scheme for the investigated water bodies should cover the entire local ecosystem and it should involve the protection of the littoral zone, determination of protected areas, inhibition of the sedimentation process which speeds

up eutrophication or the physical removal of deposits and their evacuation outside the floodplain area.

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STRESZCZENIE

Znaczenie starorzeczy dla ekosystemu zalesionych dolin rzecznych

Słowa kluczowe: *azot, fosfor, ochrona wód, osady denne, retencja leśna, retencja wód, starorzecza*

Zainteresowanie funkcją, jaką pełnią obszary leśne w poprawie jakości wody, wzrastało od kiedy bariery biogeochemiczne stały się efektywnym narzędziem przeciwko zanieczyszczeniom obszarowym, wprowadzanym do wód powierzchniowych. Wzdłuż dolin rzek meandrujących pojawiają się liczne jeziora równin zalewowych jako cenne ekosystemy wodne, lecz o zaawansowanym stopniu eutrofizacji. Ich poziom troficzny zależy nie tylko od stopnia połączenia z rzeką, ale również od użytkowania przyległego obszaru. Badania prowadzone nad ekosystemami wodnymi rzek północnej części kraju przyczyniły się do poznania roli, jaką odgrywają obszary zalesione w migracji zanieczyszczeń w dolinie Łyny. Badania dotyczyły sezonowej zmienności koncentracji azotu i fosforu oraz właściwości osadów dennych w odniesieniu do zmiennych warunków hydrologicznych. W kontekście lokalnych warunków hydrologicznych, geologicznych i topograficznych zasilanie starorzecza ma różny charakter. Oscylacje poziomu wody w zbiorniku w cyklu rocznym w zakresie dochodzącym do ponad 200 cm determinowała ponad 5-krotną zmienność jego objętości i zdolności retencyjnej. Jednakże jakość wody w zbiorniku była uwarunkowana zasilaniem przez wody rzeki, istotny udział w zasilaniu zbiornika miały wody gruntowe zbocza doliny i wody aluwialne przesiąkające z koryta rzecznego. Ich udział jest zmienny w czasie i zależy bezpośrednio od wielkości przepływu w rzece i poziomu wód w dolinie, przepuszczalności utworów aluwialnych oraz rzeźby terenu. Erozja stromej skarpy brzegu wklęsłego zbiornika odpowiadała za duży spływ azotu i fosforu do jego wód. Procesami generującymi

depozycję osadów dennych w starorzeczach były produkcja pierwotna i wtórna oraz wezbrania rzeczne. Bilans materii w zbiorniku odpowiadał za przynajmniej 10-krotnie szybszy przyrost osadów niż w jeziorach glacjalnych. Przyśpieszony proces odcinania, wypłycania i zalądowienia cennych ekosystemów wymusza konieczność ochrony w odniesieniu do funkcji, jakie pełnią one w krajobrazie leśnym.

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