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THE USE OF A GEOCHEMICAL METHOD IN THE DETECTION OF GROUNDWATER DISCHARGE TO FLOODPLAIN LAKES

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Abstract

Water quality parameters of floodplain lakes may be indicative of the intensity of groundwater recharge. The main assumption made in the study is that the direct influence of groundwater recharge is reflected in the vertical gradient of temperature and aeration along the whole water column. Considering this, we seasonally monitored physical and chemical properties of 22 oxbow lakes in postglacial river valleys (the Słupia, Drwęca and Łyna rivers) in temperate climate zone in the southern watershed of the Baltic Sea (N Poland). The results were compared with groundwater samples from transects of piezometers located near the floodplain lakes. The floodplain water bodies showed variability (both in vertical and spatial dimensions) in temperature, aeration and electrolytic conductivity, affected mainly by different sources of water supply. The temperatures and dissolved oxygen contents declined not only with the increasing depth of water and a distance from the river channel, but also a significant drop in the parameters' values have been associated with groundwater recharge within the floodplain edge.

Key words: oxbow lake, groundwater, hydrological connectivity, thermal gradient, aeration

INTRODUCTION

The behavior of freshwater ecosystems and associated hydrologic characteristics are derived primarily from the basin they drain (e.g., Hynes 1975, Mazurek 2000). There are numerous factors such as climate, tectonics, topography, lithology etc. that either individually or in combination influence two complementary processes of chemical weathering and mechanical denudation (Meybeck 1987, Berner and Berner 1996, Walling and Webb 1983). The relative importance of these factors is still poorly known. Physical and chemical characteristics of a stream are controlled by physical watershed characteristics and the interaction of precipitation, surface runoff, and groundwater with this matrix of watershed characteristics (Hillbricht-Ilkowska 1994, Glińska-Lewczuk 2006). Water flow in alluvial floodplains is characterized by highly complex, multidimensional exchange pathways under the term 'hydrological connectivity'. It operates on the four dimensions of fluvial hydrosystems: longitudinal, lateral, vertical and temporal (Amoros and Bornette 2002, Ward et al. 2002). In a study of rivers in large alluvial aquifers by Larkin and Sharp (1992) it is showed that groundwater flow could be base flow, under flow, or mixed flow, depending on the slope, sinuosity, and depth of penetration of the river in the aquifer. This attribute is particularly important for floodplain water bodies, to which lateral connectivity guarantees the surface water exchange through the links to the main course of a river. However, the key factor influencing ecohydrology of floodplain lakes is vertical connectivity that assures the exchange between the surface and groundwater via infiltration into the alluvial aquifer and exfiltration of phreatic water from the hillslope aquifer.

The amount of water that the oxbow receives from each of these depends on (i) the size and land use of the watershed, (ii) the position of the wetland in respect to the surface topography and (iii) the groundwater table (Tockner and Stanford 2002). For this reason, in spite of close spatial arrangement along one floodplain, they may undergo different rates of dynamic changes, succession and evolution. Apart from groundwater recharge, the degree of connectivity with one parent channel is a key factor in susceptibility of a floodplain lake to the rate of development (Amoros and Bornette 2002, Glińska-Lewczuk 2009, Ward et al. 2002).

The diversity of floodplain lakes is related to the regular and repeated rejuvenation of the aquatic environments (Petts 1990) and is commonly attributed to the disturbance regime of floodings. Nevertheless, four sources of water are recognized as contributing to floodplain water dynamics: lateral overflow, groundwater, upland sources and direct precipitation (Tockner and Stanford 2002, Anibas et al. 2011). The chemical composition of groundwater is a function of hydrogeochemical processes acting within the catchment. Thus, the annual mass balance of dissolved and suspended solids transported by rivers can be used to characterize and quantify the chemical and mechanical erosion in their drainage basins.

Differences in the intensity of groundwater recharge contribute to the spatial heterogeneity of water quality in floodplains and they can be measured with various *in situ* techniques. Many indicators of ground-water discharge to surface water can be used to determine specific localities where a given contaminant may enter a surface water body. The most common indicators are: seeps and springs, infrared mapping, aquatic plants, benthic organisms, phreatophytes, unique sediment zones such as mineral precipitates, water color; odor from contaminants; and mapping of lineaments in fractured-rock settings. None of these methods is satisfying to identify specific localities where high quality groundwater discharges to a water body. An interesting method proposed also Chormański et al. (2011) who successfully tested remote sensing techniques in the identification of water origin in the conditions of the Biebrza River (NE Poland) floodplain.

An unexploited method still seems hydrochemical detection of water origin. Hydrochemical profiling along waterbodies make possible to establish the share that various factors have in supplying the river channel with water. A detailed vertical and spatial monitoring of water quality parameters with the use of multiparameter sondes can be effective tool for the groundwater recharge detection. An advantage of using this hydrochemical *in situ* technique is the recognition of local sources of man-made pollution.

The nature of groundwater supply depends on the differences in morphology of the river valley as well as hydrogeomorphic processes of fluvial origin. Within high gradient systems, hillslope erosion processes determine the rate of supply of sediment to the channel and, hence, the temporal evolution of riparian habitats. However, alluvial low gradient river systems with extensive floodplains are located further downstream in the longitudinal river continuum; and they are most strongly influenced by hydrogeomorphic processes of fluvial origin. They may contain riparian zones primarily reflecting species-specific responses to soil moisture/oxygenation, sediment deposition, the frequency and duration of inundation, and the erosive action of flooding along a lateral gradient (Ward et al. 2002).

Gradients between surface (river) and groundwater result from the mixing of water with different physicochemical characteristics and biogeochemical processes in conjunction with the local residence time of water. In case of floodplain lakes, a direct influence of groundwater recharge is ultimately related to the vertical stratification of temperature, light and aeration of the whole water column. In summer, a groundwater recharge with colder and low aerated water decreases intensity of biogeochemical processes in lotic and lentic floodplain lakes, such as diffusive exchange at the sediment – water interface, decomposition of organic matter and algal photosynthesis. Small changes in the relative contribution of individual water sources may drastically alter species composition and species diversity. For example, local groundwater upwelling is often associated with a higher standing crop of algae, higher zoobenthos biomass, faster growth rates of floodplain trees and a higher species richness of woody and herbaceous plants (Obolewski 2011).

It has been reported (Chormański et al. 2011) that during floodplain inundations, when the water level in the channel exceeds the bankfull level, surface connection of all waterbodies causes more or less similar concentrations at all locations across the inundated river landscape. Dissolved nutrients are at intermediate levels, and subsurface recharge during this phase is not distinct. Suspended solids concentrations, exhibit a wide range, reflecting the heterogeneous pattern of current velocities. These processes are rapidly altered as the water level recedes and surface connections are severed. During the disconnection phase distinctive water bodies characterize the riverine landscape with internal (autogenic) processes dominating (e.g., nutrient uptake, grazing). According to the Ward's concept (Ward et al. 2002), during the seep-

age connection phase the river and floodplain are connected via subsurface pathways. Large amounts of nutrient-rich ground water enter the flood plain, yet retention is relatively high. This is the 'primary production phase', during which periodic nutrient pulses (via seepage flow) stimulate algal production. When the river and its floodplain are interconnected by surface water, hydrological exchange processes dominate because the majority of particulate matter is transported during this high-water period. Therefore, there are spatial and temporal shifts in functional processes across the riverine landscape.
The aim of the presented paper is to show that the detailed survey of physical and chemical parameters of water along floodplain lakes is an effective method of the detection of external water supply to floodplain water bodies.

MATERIAL AND METHODS

Study sites

The present study was conducted in the meandering sections of three rivers of Southern Baltic Sea (N and NE Poland: the River Łyna (Fig. 1) located 25 km north of Olsztyn – the largest city in the Warmia and Mazury region between the villages of Smolajny and Łaniewo; the Drwęca River upstream to the village of Bratian and the Słupia River above the city of Słupsk. The distances between external oxbows within each floodplain are less than *ca.* 12 km.

Table 1

Selected characteristics of the three investigated rivers along meandering stretches: the Łyna River (at Smolajny), the Drwęca River (at Rodzone) and the Słupia River (at Słupsk)

Parameter	Unit	River – cross-section		
		Łyna – Smolajny	Drwęca – Rodzone	Słupia – Słupsk
River length from the outlet	L, km	172.0	126.7	31.6
Watershed area	A, km^2	2,290	2,725	1,450
Mean annual discharge	Q_{avr}, m^3 s^{-1}	14.7	11.2	15.0
Decennial flood discharge	$WQ_{10\%}$, m^3 s^{-1}	50.5	46.1	49.0
Discharge variability coefficient	Cv, -	0.439	0.442	0.450
Range of water stages	H, cm	207	191	171
Channel slope	I, m km^{-1} or %%	0.32	0.30	0.18
Average valley width	W_v, m	372	618	315

The studied river corridors in northern Poland are of high ecological quality with flow volumes depending on the mixed type of hydrological regime (sensu Pardè) with generally low runoff per unit area (5-7 $l \cdot km^{-2} s^{-1}$), due to moderate rainfall totals (620 mm on average) and high evapotranspiration values. Presented river sections are characterized by the discharges of the same order of magnitude (from 11 $m^3 s^{-1}$ for the Drwęca to 15 $m^3 s^{-1}$ for the Słupia River) draining the areas of 1,450-2,725 km^2 (Table 1).

In general two distinct periods of accelerated water exchange are observed during a year in northern Poland: spring snow melting and summer intensive rainfalls. The bottoms of the river valleys are usually flooded in the spring months due to the snowmelt. Summer floodings do not occur due to the intensive evapotranspiration and high retention capacity of the catchments. The latter derives from gentle slopes,

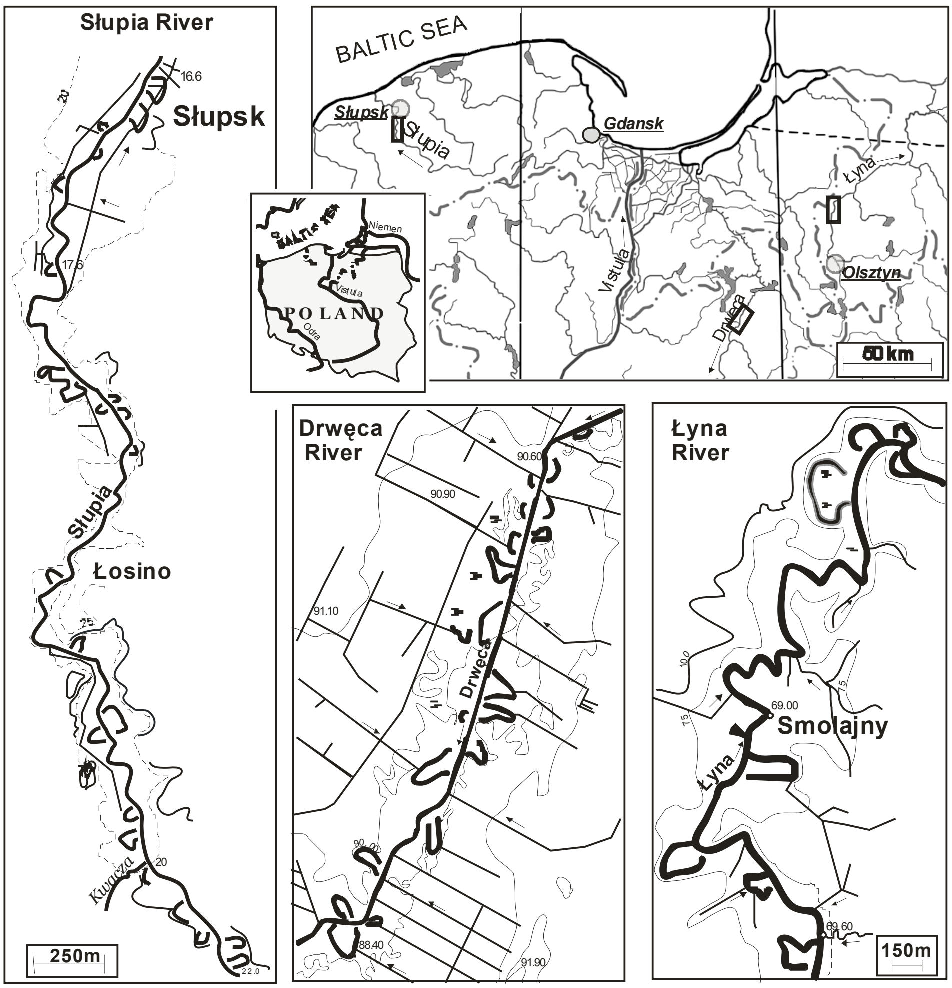

Fig. 1. Location of the studied rivers and floodplain lakes on the background of map of N Poland

numerous lakes together with thick podzolics soils, what results in attenuation of flood waves, predominance of groundwater outflow and prevailing vertical movement of soil water through the upper soil horizons. There is an evidence, however, that groundwater contributions to the runoff regimes of postglacial watercourses are significant due to inputs from subsurface postglacial aquifers.
The research comprised oxbow lakes within the alluvial and relatively young from geological point of view (the Baltic glaciation, Pomeranian Phase), river valleys. In the river valleys, prevail proper alluvial soils, humous alluvial soils derived from sands and silts as well as peat-mud soils. On the areas adjacent to the bottom of the valley one may found brown and deluvial soils derived from loams, silts and clays. The slope of the valleys is covered also by rusty soils, arenosols and deluvial soils derived from sands.
The river landscape has changed over the last century. In the first half of 20^{th} century, the studied sections of the rivers were reclaimed (straightened) to improve the outflow of water. In the consequence of the regulation, numerous oxbow lakes appeared in the valleys. These artificially created water bodies are characterized by permanent water table, in contrast to those, naturally formed as a consequence of the fluvial processes.

Measurements and methods

The measurements were done *in situ* in 22 floodplain lakes located in 3 valleys of the Słupia (6), Drwęca (6), and Łyna rivers (10). For the purpose of this study, oxbow lakes were divided into 3 groups with respect to the degree of hydrological connectivity: lotic, semi-lotic and lentic (Glińska-Lewczuk 2009a). The studied foodplain lakes are described in detail by Glińska-Lewczuk (2009b).
Monitoring of water quality parameters in floodplain lakes as well as hydrochemical vertical distribution of the parameters have been performed using Multi-Parameter Water Quality YSI 6600 equipped with the following physicochemical sensors: temperature T, dissolved oxygen (DO), pH, redox potential (ORP), specific electrical conductivity (SEC), total dissolved solids (TDS), NH_4-N, NO_3-N, Cl^-, salinity, turbidity, chlorophyll. At least three or four points along the aquatic zone of each waterbody and in the adjacent rivers, were measured. Regular seasonal measurements taken over a period of 3 years were necessary to determine if the water chemistry of oxbow lakes was consistent.
Differences in the parameters along each channel provided information on possible groundwater seepage. By comparing results of the measurements we evaluated the potential groundwater influences on the water quality of the lakes. At locations where the measurements results in the vertical profile varied significantly from the measurements performed in the other parts of a given oxbow and the adjacent river, we recognized that site as groundwater fed. At this sites, we monitored also groundwater samples from transects of piezometers set-up perpendicularly to a valley axis. In the paper we present results obtained from two transects located in the Łyna River valley judged as the representative for the illustration of the processes observed.
The relative importance of ground water and hydrological connectivity for explaining the variation in water quality parameters was evaluated by using multivariate

techniques. These multivariate analyses allowed for the comparison of different environmental variables (i.e. lateral connection with the river channel, distance from the river, depth, physical and chemical parameters). The ordination was carried out using Canoco 4.5 (Ter Braak 1995). Ingradient analyses of PCA (Principal Component Analysis) were performed using default (standard) options. Log-transformed hydrochemical dataset was used (Ter Braak and Smilauer 2002). Analysis of variance (one and two-way ANOVA) was performed with the Duncan's test at $P \leq 0.05$ (Statistica 10.PL).

RESULTS AND DISCUSSION

Considering the processes related to the lateral or vertical connectivity of floodplain lakes, we observed seasonal changes in physical and chemical properties of the ecosystems in postglacial river valleys in temperate climate zone in northern Poland. The diversity of physico-chemical parameters of water supplying the oxbow lakes and their temporal changes are indicative of various origin and intensity of water supply.

Water temperature. The most distinct feature of the various sources of water supplying floodplain lakes is water temperature. It may significantly differ among both water bodies within the same floodplain as well as within the same water body at any given time. Temperatures of oxbow lake water showed a typical, seasonal pattern for the temperate climatic zone, with minimum values of > 0.3°C in January and February and maximum values in July > 20°C.

This thermal diversity results from both the different origins of the water and the distance from the river channel. The most distinct gradients of surface water-groundwater phase have been stated to lentic and semi-lotic environments due to the reduced current velocity. The most extreme differences between surface and the bottom were found in summer. As it is showed on the example of the SS-2 lentic water body in the Słupia River, (Fig. 2) downstream arm exhibited bottom temperatures about 3-4°C lower in summer, whereas 1-2°C higher in winter than the most remote site from the river. Summer temperatures just below the surface (0-25 cm) of the oxbow lake were similar due to wind mixing and leaves shadows.

Floodplain lakes at the sites where the groundwater recharge exhibits significantly lower temperatures at the bottom, according to Tockner and Stanford (2002) may serve as 'cold-water' refugia for biota. An example of SS-2 shows temperature of water lower by 10°C when compared to the river channel. This interesting phenomenon of "cold-spot" in the floodplain lake is characterized by significantly lower DO saturation of water (*ca.* 1.00 mg O_2/l) and relatively higher SEC values (400 µS/cm).

Among the 3 types of oxbow lakes, the widest range in mineralization showed lentic reservoirs. Similarly to other types of oxbow lakes, vertical profiles of specific conductivity had highest values at bottom. However, the distribution of near-bottom SEC is very sensitive to the groundwater supply. Based on the example of lentic oxbow lake presented in Fig. 3, at the most remote site from the river, where groundwater is characterized by a significantly higher SEC level, we noted the increase in this parameter to 400 µS/cm when compared to 240 µS/cm at the downstream

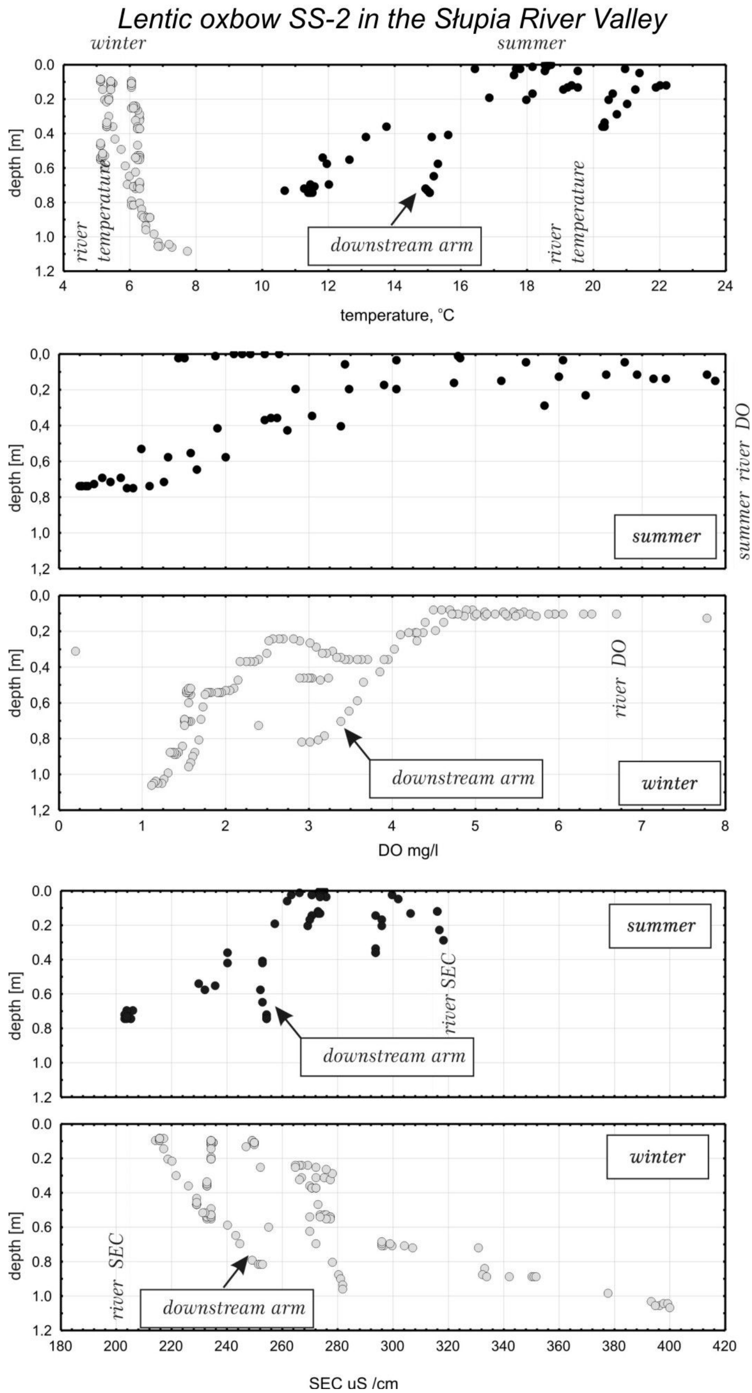

Fig. 2. An example of summer and winter vertical profiles of selected water quality parameters (T, DO and SEC) in the lentic oxbow lake SS-2 in the Słupia River Valley characterized the highest gradients, since measured

arm and 280 μS/cm at the upstream arm. In the light of above, higher specific conductivity and lower pH values in closed oxbow lakes when compared to the river water could be satisfying indicators of groundwater supply.

Dissolved oxygen profiles throughout the study sites were not stratified, although there were substantial differences in DO concentrations among habitat types. The water column at lentic sites was poorly oxygenated. The oxygen content declined with increasing depth of water and lateral distance from the river channel (Fig. 2). The effect of backward input of river water via downstream arm to semi-lotic oxbow lakes significantly increases and stabilizes water aeration. The group of lentic oxbow lakes suffered from long-term oxygen deficits embracing the entire water column particularly in summer and in winter when ice cover prolonged. Any available oxygen particles immediately take part in numerous biogeochemical reactions and respiration of the organisms. As the alluvial aquifers tended to be sub-oxic, as shown in Fig. 2, by relatively low dissolved O_2 and ORP, groundwater does not recharge the ecosystem in this gas. Oxygen deficits are common in lentic and semi-lotic water

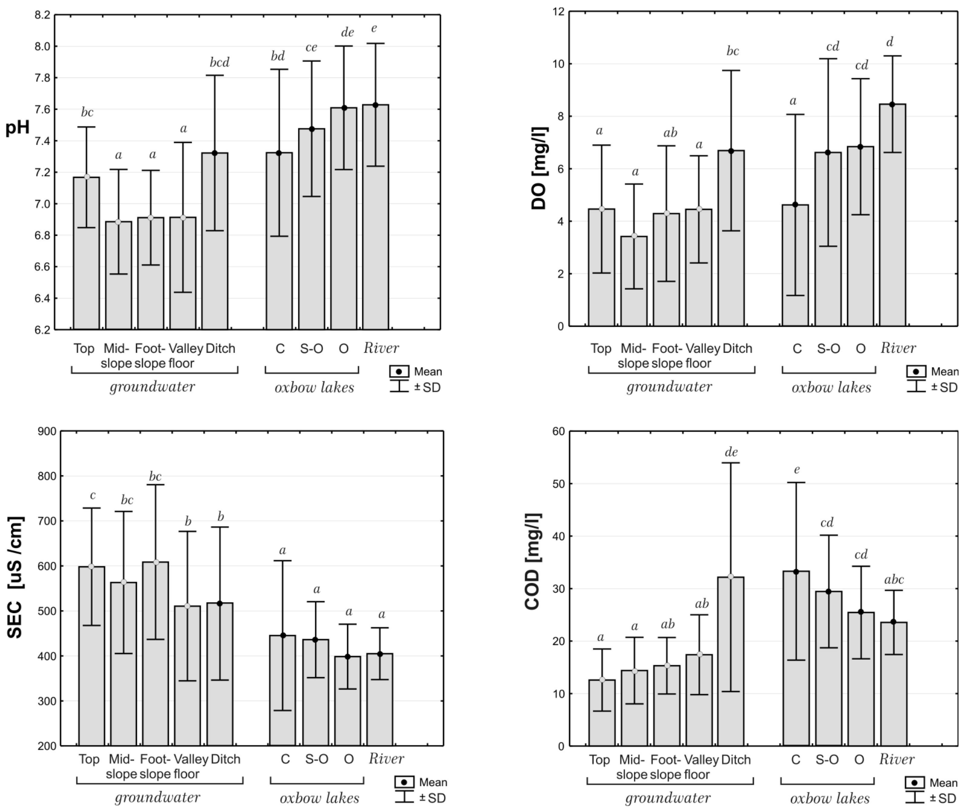

Fig. 3. Variability in selected physical parameters of groundwater and water of water bodies within the studied meandering sections of the Słupia, Drwęca and Łyna river valleys. C – denotes closed (lentic) oxbow lakes, S-O – semi-open (semi-lotic) and O – open (lotic) oxbow lakes. The same letters denote groups of homogeneous means (ANOVA), not different in the Duncan's test at $P \leq 0.05$

bodies due to biogeochemical processes, and it is difficult to indicate directly the influence of low-saturated groundwater. However, in summer at the river remote vegetation-free sites, DO contents lower by 1-2 mg/l were recorded (Fig. 3), when compared to downstream arms. No significant differences in terms of DO content were found between the vegetated sites and the groundwater supplied vegetation-free sites. In lentic reservoirs, chlorophyll and turbidity may be co-indicators of groundwater recharge. They mainly depend on the phytoplankton development, which is controlled by the oxygen and light conditions as well as nutrient content in the water.

The amount of **suspended solids** and the consequent turbidity depend mainly on the origin of the water. Groundwater is characterized by a very low suspended load while rivers transport a lot of suspended matter. It can be seen a progressively higher load of suspended solids together with a decreasing organic content with increasing connectivity to the main channel. Water bodies where groundwater supply prevail (lentic) showed a very low suspended load while the channels bi-connected with the river showed markedly higher concentrations of suspended matter.

In lentic lowland waterbodies, **turbidity** mainly depends on phytoplankton development, which is controlled by the nutrient content of the water (not shown in the figure). Within semi-lotic lakes, still connected at their downstream end, longitudinal gradients of turbidity decreased with distance to the main river, as a result of river backflow. The data demonstrated increasing groundwater supply and effectively diluting nutrient concentrations could initiate regression from a highly eutrophic state to a mesotrophic.

Nutrient content. In water of the studied oxbow lakes, the nutrient content of groundwater origin is superimposed by other factors depended on the retention time of the water and nutrient uptake by primary producers. Seepage from hillslope aquifiers beneath agriculturally used areas is nitrate-rich by three times higher at top- and mid-slope (1.23 and 1.32 mg N/l, respectively) than those locations at footslope and alluvial aquifers or river water. Nevertheless, alluvial aquifer provide relatively nutrient-poor water, the concentrations of NO_3-N concentration in disconnected waterbodies, also depends on surrounding land use and successional stage.

PCA on physico-chemical parameters of water in the floodplain water bodies and environmental variables explained 49.08% of the variance in time (Fig. 4). All parameters involved in biochemical processes as nitrates, pH, dissolved oxygen (ORP) were strongly negatively correlated to the distance from the river and depth of the water body. SEC, salinity and NH_4-N were grouped on the first axis which corresponds to the distance from the river but they are negatively correlated to redox potential (ORP). Suspended solids were positively correlated to the second axis which was linked to the environmental variables, including hydrological connectivity of a given water body, a distance of a sampling point from the river as well as the oxbow's depth. PCA also showed an opposite trend between nitrates, turbidity and chlorophyll in the oxbow lake water and TDS. The multivariate method (PCA) confirmed the significance of vertical hydrological connectivity as the main factor responsible for the dynamics of physicochemical parameters of water in each floodplain lake.

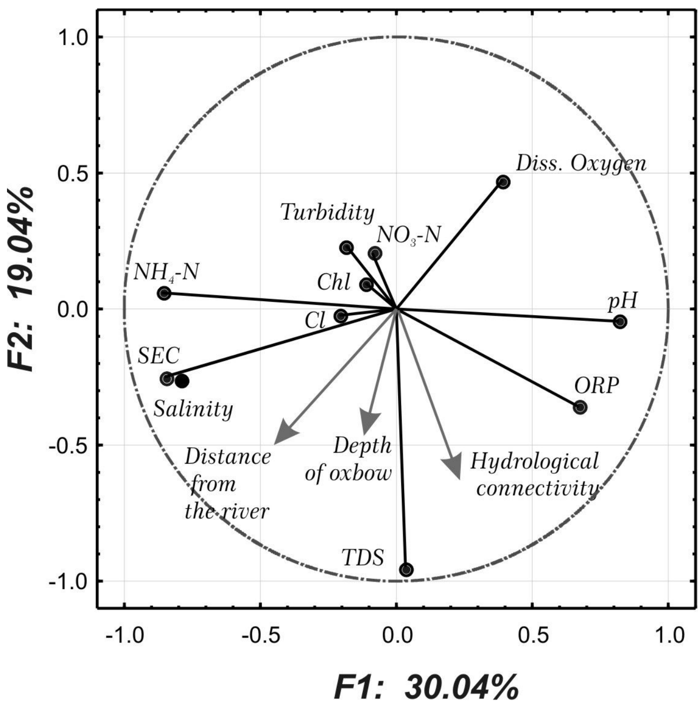

Fig. 4. Results of the principal component analysis (PCA) between environmental (nominal) variables and physico-chemical parameters of oxbow lakes water

CONCLUSIONS

River water, especially at higher stages (e.g. floods), and groundwater can synergistically influence oxbow trophic state. When the oxbow lake is intensively supplied by groundwater nutrient-poor, its water gets more meso- or oligotrophic, what was also described by Piégay et al. (2001). The lack of nutrients may constrain the rate of eutrophication of the oxbow lake, and limit the contribution of organic matter to the in-filling of the basin. Oxbow lakes with a regular groundwater supply tend to fill in at relatively slower rates than those without a supply (Piégay et al. 2001).

High gradients of temperature, dissolved oxygen contents in some vertical profiles oxbow lakes indicate active exchange of ground and surface water. It is the evidence that those waterbodies must exist with a sufficient discharge potential of alluvial or hillslope aquifers.

So high gradients as presented in case of oxbow SS-2 meet the conditions listed by Amoros and Bornette (2002):

(i) hillslope alluvial aquifer must exist with a sufficient discharge potential,
(ii) the slope within the water body must be steep enough to drain groundwater out from the aquifer and release it downstream,
(iii) the impact of the expected groundwater drainage on the surrounding water tables must be assessed and found to be acceptable.

Our data demonstrated, that nutrient-poor groundwater supply may have a diluting effect on nutrient concentrations in floodplain ecosystems and could initiate regression from a highly eutrophic state to a mesotrophic. When the oxbow lake is intensively supplied by nutrient-poor groundwater, its water gets more meso- or oligotrophic, what was also described by Piégay et al. (2001). Lower nutrient concentrations may constrain the rate of eutrophication of the oxbow lake, and limit the contribution of organic matter to the in-filling of its basin. Oxbow lakes with a regular groundwater supply tend to fill in at relatively slower rates than those without the supply (Piégay et al. 2001).
Our research confirmed the hydrochemical method can be a reliable tool is assessing groundwater supply of floodplain water bodies. The proper and sensitive multi-parameter probes are useful tools in water quality monitoring but also in identification of point source of groundwater recharge. The use of hydrochemical method detecting groundwater – surface water interactions shows an effective and cost effective approach. Identification of the changes in the spatial heterogeneity of surface water properties with the use of *in situ* multiparameter sondes is a direct method that should be employed in the contemporary management activities required at destroyed wetlands, lakes and rivers. In light of presented problem, the current challenge for hydrochemists is to assist ecologists in identifying potential problem discharge zones so the toxicological impacts on benthic and hyporheic aquatic life can be assessed.

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ZASTOSOWANIE METODY GEOCHEMICZNEJ DO IDENTYFIKACJI ZASILANIA PODZIEMNEGO STARORZECZY

Streszczenie

Parametry jakości wód w jeziorach rzecznych mogą być traktowane jako indykatory intensywności zasilania podziemnego. Głównym założeniem prowadzonych badań był bezpośredni wpływ zasilania podziemnego na jakość wód starorzeczy zidentyfikowany na podstawie gradientu temperatury i natlenienia wody w przekrojach pionowych i podłużnych zbiorników. Uwzględniając tę hipotezę, monitoringowi poddano właściwości fizyczne i chemiczne wody w 22 starorzeczach północnej Polski (w dolinie rzeki Słupi, Drwęcy i Łyny) położonych w umiarkowanej strefie klimatycznej, w warunkach fizyczno-geograficznych południowego zlewiska Bałtyku.

Wyniki uzyskane z monitoringu wód starorzeczy porównano z jakością wód gruntowych badanych w piezometrach położonych w pobliżu jezior rzecznych. Badane zbiorniki charakteryzowały się dużą zmiennością cech fizykochemicznych, głównie natlenienia, przewodno-

ści elektrolitycznej wynikającej z różnych źródeł pochodzenia wody. Badania wykazały, że zarówno temperatura, jak i koncentracje tlenu rozpuszczonego zmniejszają się nie tylko wraz ze wzrostem głębokości zbiorników i odległości względem rzeki, ale także znaczący spadek tych wskaźników związany jest z zasilaniem gruntowym u podnóży krawędzi dolin rzecznych.