The effect of groundwater supply on the hydrochemical diversity of flood plain lakes in the temperate climatic zone

KATARZYNA GLIŃSKA-LEWCZUK[1], SZYMON KOBUS[1], KRYSTIAN OBOLEWSKI[1] & JAROSŁAW CHORMAŃSKI[2]

1 *Department of Land Reclamation and Environmental Management, University of Warmia and Mazury in Olsztyn, Plac Łódzki 2, Poland*
kaga@uwm.edu.pl

2 *Division of Hydrology and Water Resources, Warsaw University of Life Sciences, Poland*

Abstract In this paper we investigate the spatial heterogeneity of chemical parameters within flood plain lakes with different ground and river water recharge intensities. We assumed that the direct influence of groundwater recharge is ultimately related to the vertical stratification of temperature and aeration of the whole water column. Accordingly, we seasonally monitored physical and chemical properties of 22 oxbow lakes in the postglacial river valleys of the Słupia, Drwęca and Łyna rivers of Poland. The results were compared with groundwater from transects of piezometers located near the oxbow lakes. The flood plain water bodies showed variability (both in vertical and spatial dimension) in temperature, aeration and specific conductivity, affected mainly by lateral connectivity to the river. The temperatures and oxygen contents declined with the increasing depth of water and distance to the river channel. The detected differences in vertical gradients of physico-chemical parameters within one reservoir, or a group of those, confirmed the evidence of groundwater recharge.

Key words oxbow lake; groundwater; hydrological connectivity; thermal gradient; aeration

INTRODUCTION

Water flow in alluvial flood plains 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 (Ward, 1989; Kondolf *et al.*, 2006). The diversity of flood plain 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 (Galat *et al*., 1998). Nevertheless, four sources of water are recognized as contributing to flood plain water dynamics: lateral overflow, groundwater, upland sources and direct precipitation (Tockner & Stanford, 2002).

The role 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 (e.g. Swanson *et al*., 1982). However, alluvial low-gradient river systems with extensive flood plains are located further downstream in the longitudinal river continuum; and they are the 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 (Tockner *et al.*, 1999).

Differences in the intensity of groundwater recharge contribute to the spatial heterogeneity of water quality in flood plain water bodies (Amoros & Bornette, 2002). Gradients between surface and groundwater result from the mixing of water with different physicochemical characteristics and biogeochemical processes, in conjunction with the local residence time of water. The direct influence of groundwater recharge is ultimately related to the vertical stratification of temperature, light and aeration of the whole water column. Biogeochemical processes in lotic and lentic flood plain lakes, such as diffusive exchange at the sediment–water interface, decomposition of organic matter and algal photosynthesis, are influenced by physical and chemical gradients in the water column. In addition to lateral connectivity that links the main course of a river with flood plain water bodies, the key factor influencing ecohydrology of flood plain 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 aim of the paper is to investigate the relative contribution of river and groundwater, and their influence on the chemical composition of flood plain lakes in the temperate zone of northern Poland. Depending on the spatial heterogeneity of water between and within flood plain lakes, we tried to detect physical and chemical parameters of water that are the most sensitive to any hillslope and alluvial aquifers recharge.

MATERIAL AND METHODS

Study site

The study was conducted in the meandering sections of three rivers of northern Poland: the Łyna River (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 flood plain are less than approx. 12 km.

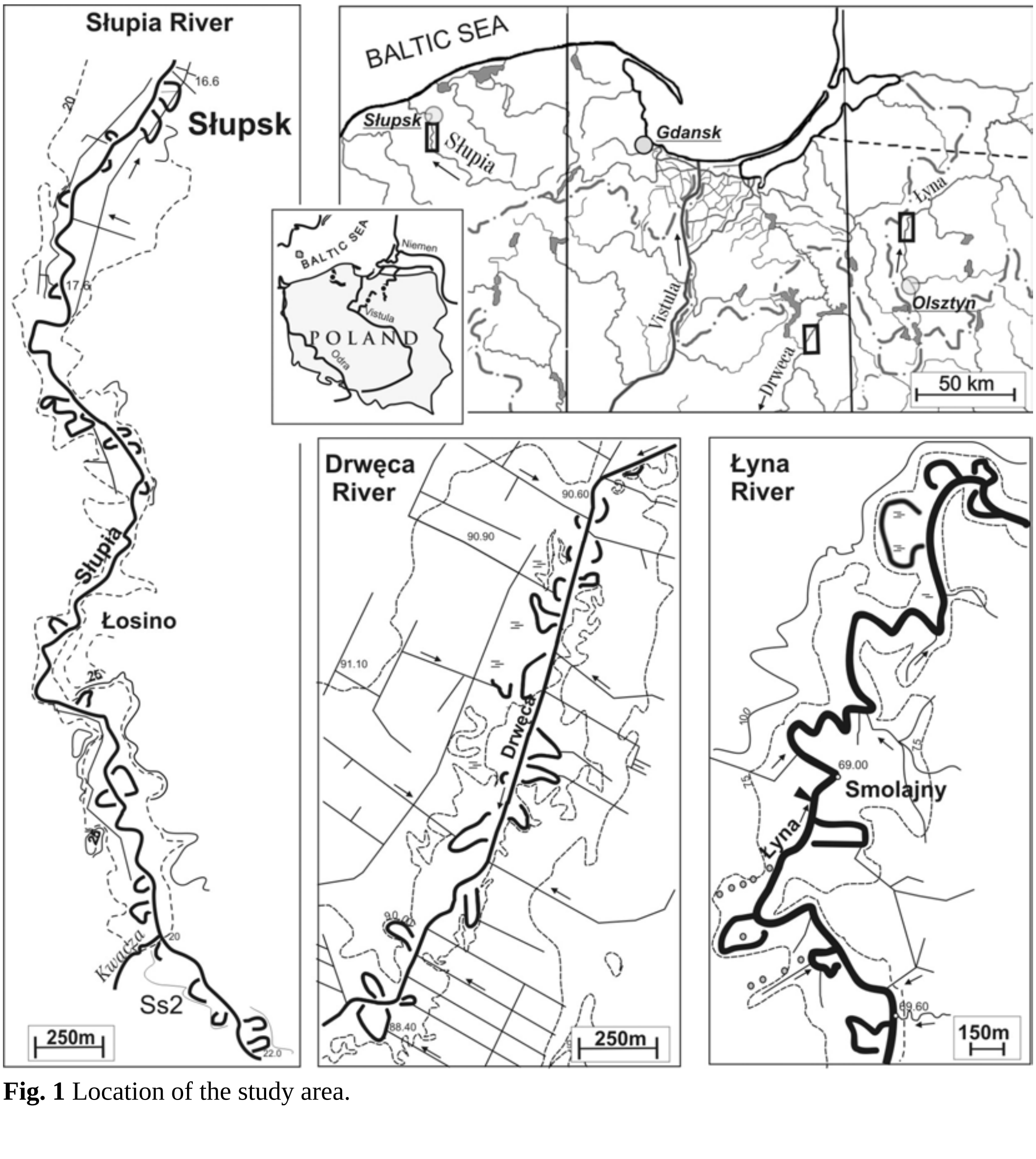

Fig. 1 Location of the study area.

The studied river corridors in northern Poland are of high ecological quality, with flow volumes depending on the mixed type of hydrological regime. Runoff per unit area in lowland areas in Poland is generally low (5–7 $L \cdot km^{-2}\ s^{-1}$), due to moderate rainfall totals (620 mm on average) and high evapotranspiration rates. The presented river sections are characterized by 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 1450–2725 km^2 (Table 1).

Table 1 Chosen 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	2290	2725	1450
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
Channel sinuosity	S, after channelization	1.36	1.66	1.21
	S, before channelization	1.82	2.40	2.13
Average number of oxbow lakes per/1 km of the valley length	No·1 km^{-1}	3	10	4

In catchments of north Poland, usually two distinct periods of accelerated water exchange are observed during a year: spring snow melting and summer intensive rainfalls. The bottoms of the river valleys are usually flooded in the spring months due to the snowmelt. In contrast to the mountainous rivers of southern Poland (i.e. the upper Oder River tributaries) summer floodings do not occur due to the intensive evapotranspiration and high retention capacity of the catchments. The latter derives from the gentle slopes, and numerous lakes together with thick podzolics soils, which result in attenuation of flood waves, predominance of groundwater outflow and prevailing vertical movement of soil water through the upper soil horizons. However, there is evidence that groundwater contributions to the runoff regimes of postglacial watercourses are significant due to inputs from subsurface postglacial aquifers.

The research investigated oxbow lakes within the alluvium, which are relatively young river valleys from a geological point of view (the Baltic glaciation, Pomeranian Phase). 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 find brown and deluvial soils derived from loams, silts and clays. The slope of the valleys is also covered by rusty soils, arenosols and deluvial soils derived from sands. In bi-connected water bodies, the substratum usually ranges from medium to coarse-grain mineral sediment (i.e. sand, gravel or pebbles), depending on the frequency of connection and scouring flow velocity. Water bodies only connected downstream are characterized by a fine mineral sediment (clay, silt), with moderate organic content, resulting mainly from backflow inputs and deposits combined with *in situ* production and deposition of organic matter. The sediment of disconnected water bodies consists of deposits of autogenic organic matter (Glińska-Lewczuk, 2005).

The river landscape has changed over the last century. In the first half of the 20th century, the studied sections of the rivers were reclaimed (straightened) to improve the outflow of water. The consequence of the regulation was that numerous oxbow lakes appeared in the valleys. These artificially created water bodies are characterized by a permanent water table, in contrast to those naturally formed as a consequence of the fluvial processes.

The measurements were done *in situ* in 22 flood plain lakes located in 3 valleys of the Słupia (6), Drwęca (6), and Łyna rivers (10) (Fig. 1). For the purpose of this study, oxbow lakes were divided into three groups with respect to the degree of hydrological connectivity: of lotic (open), semi-lotic (semi-open) and lentic (closed) character based on the assumptions described in (Glińska-Lewczuk, 2009).

Measurements and data analysis

Using Multi-Parameter Water Quality YSI 6600 equipment 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, designed for *in situ* monitoring and profiling, we monitored the vertical distribution of the parameters. At least three or four points along the aquatic zone of each oxbow lake, and in the adjacent main channel at each reservoir, 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 between the main and former channels provided information on possible groundwater influences. By comparing results of the measurements conducted in each oxbow lake and the adjacent main channel, we evaluated the potential groundwater influences in the oxbows. At locations where the measurements in the former channel varied significantly from the measurement in the river channel, we inferred that groundwater contributed to the oxbow lake water composition at a relatively high rate. At these sites, we also monitored groundwater samples from transects of piezometers set-up perpendicular to a valley axis. In the paper we present results obtained from one transect located in the Łyna River valley, chosen as the representative for the illustration of the processes observed.

Clustering was performed using Ward's hierarchical method that is designed to optimize the minimum variance within groups. The similarities among samples were measured by the squared Euclidean distance method. The relative importance of groundwater 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 analysis of PCA (Principal Component Analysis) was performed using default (standard) options. A log-transformed hydrochemical data-set was used (ter Braak & Smilauer, 2002). The comparisons of hydrochemical parameters between the groups of ecosystems as groundwater, three groups of oxbow lakes and river water were performed using one-way analysis of variance (ANOVA) followed by Duncan test as a *post hoc* procedure (Statistica 7.1.PL).

RESULTS AND DISCUSSION

The influence of diversity of water sources that supply the oxbow lakes and temporal changes in the intensity of the supply are reflected by changes in water quality parameters of the studied ecosystems.

Water temperature

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 of >20°C.

The most distinct feature of the studied oxbow lakes is their variability in water temperature, even within the same flood plain at any given time (Fig. 2). This thermal diversity results from both the different origins of the water and the distance from the river channel. The gradients of surface water–groundwater are the sharpest in lentic and semi-lotic environments due to the reduced current velocity. The most extreme were met in summer: the differences between surface and the bottom achieved 6.61°C. As shown in the example of the lentic water body in the Słupia River (Fig. 3), downstream arms exhibited bottom temperatures 3–4°C lower in summer, whereas in winter they were 1–2°C higher than the most remote site from the river. Summer temperatures just below the water surface (0–20 cm) of the oxbow lake were of similar values.

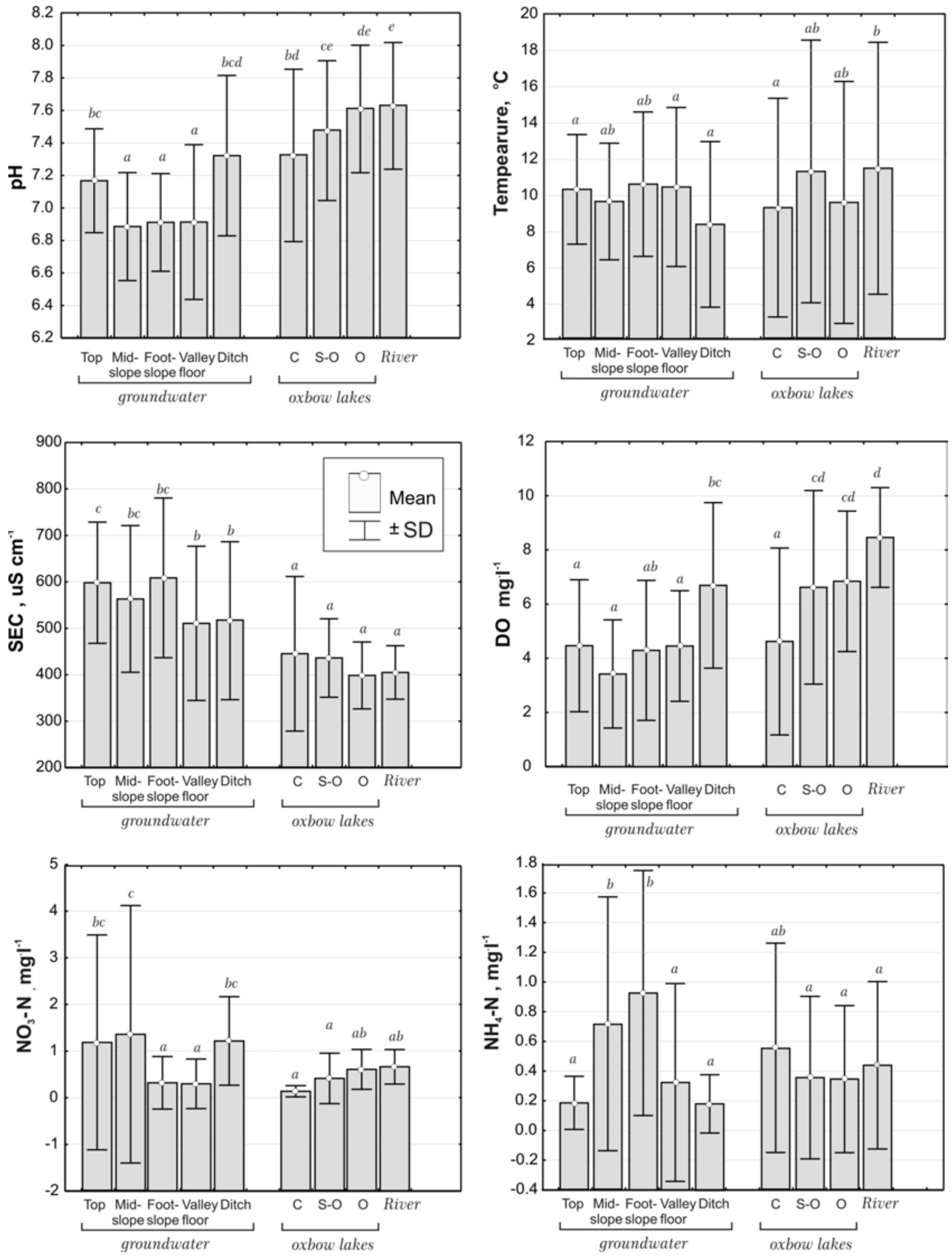

Fig. 2 Variability in selected physical parameters of groundwater and water of oxbow lakes and rivers within the studied meandering sections of the Słupia, Drwęca and Łyna river valleys. C-denotes closed (lentic) oxbow lakes, S-O – semi-open (semi-lotic) and O-open (lotic) oxbow lakes. The same letters denote groups of homogeneous means (ANOVA), not different in the Duncan's test at P<0.05.

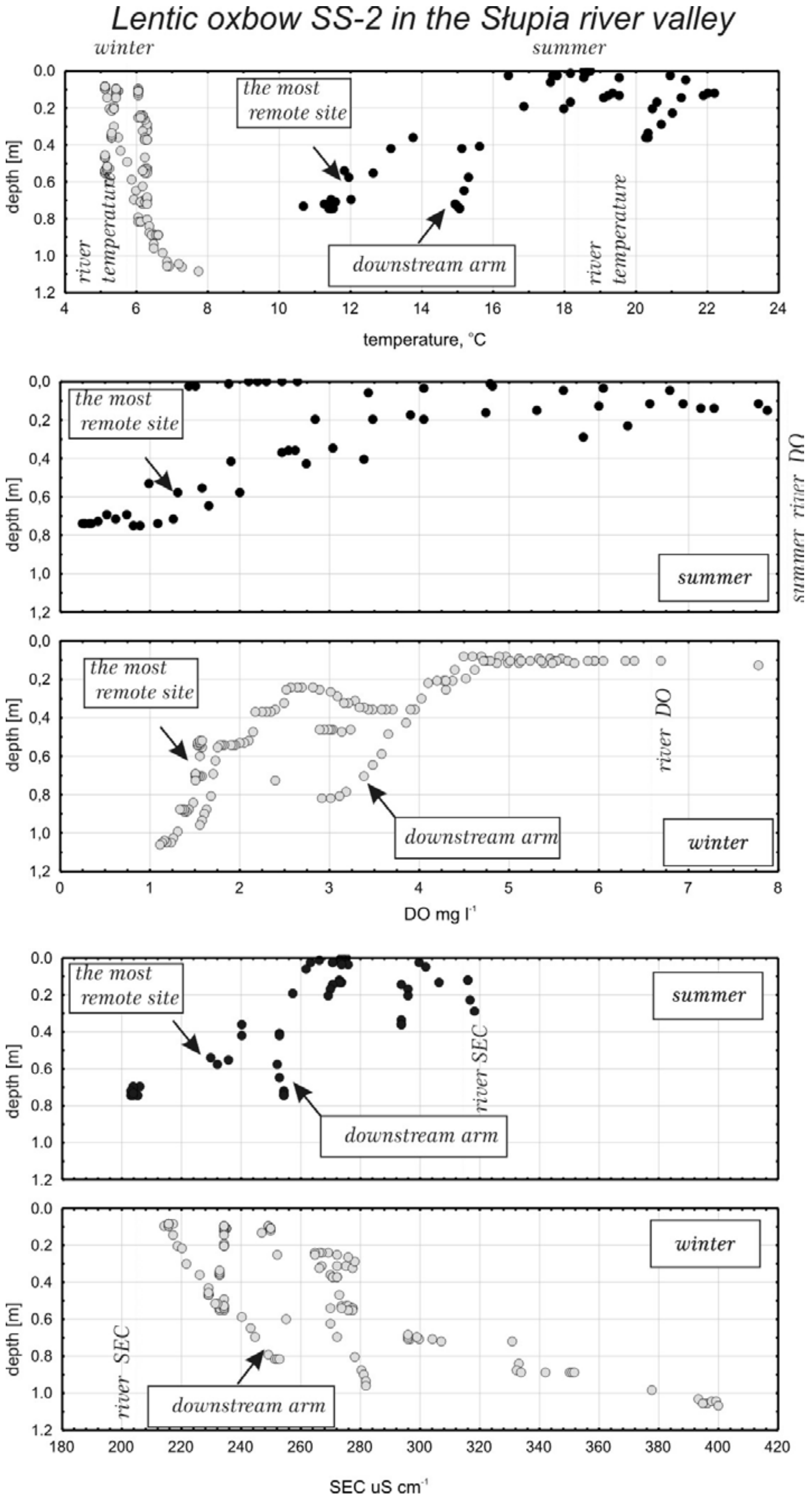

Fig. 3 An example of summer and winter vertical profiles of selected water quality parameters (T, DO and SEC) in the lentic oxbow lake SS2 in the Słupia River valley characterized by the highest gradients, since measured.

In the flood plain of the Słupia River, during one summer series of records in 2005, we noticed differences up to 8.42°C at the surficial water of oxbow lakes (from 13.93 to 22.35°C) whereas in the Łyna River we noticed thermal differences as high as 8.3°C (from 16.38 to 24.70°C). The significantly lower temperatures characterized water of lake basins deeply incised into the bottom edge of the valley hillside. Those ecosystems supplied by colder groundwater, may serve according to Tockner *et al*. (1999) as "cold-water" refugia for biota.

Water aeration

Two seasons of oxygen decrease (5.0–7.0 mg L^{-1}) and, in the case of disconnected oxbow lakes, deficiency may be distinguished: the first one during snow and ice cover (December–March) and the second one during the warm, dry summer months (June–September). The concentration of dissolved oxygen increased rapidly just after ice cover melting in early spring (April). This "deep breath" caused a short-term over-saturation achieving 13.0 mg O_2 L^{-1}. During autumn, the second period of the oxygen increase was noted, but was significantly lower in comparison to the spring period (9.0 mg O_2 L^{-1}).

Due to the intensive changes in oxygen content in oxbow lakes, all determinants connected to biochemical processes exhibited distinct fluctuations over time and demonstrated a wide range of values (Fig. 3). Dissolved oxygen vertical profiles throughout the study sites were not stratified, although there were substantial differences in DO concentrations among habitat types. The oxygen content declined with increasing depth of water and lateral distance from the river channel. In lotic environments, the river water permanent movement assured constant aeration and no deficits were recorded. The effect of backward input of river water via a downstream arm to semi-lotic oxbow lakes significantly increased 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 was 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 oxygen and ORP, groundwater does not recharge the ecosystem in this gas. In lentic and semi-lotic water bodies it is difficult to indicate precisely the influence of low-saturated groundwater, especially when the groundwater and oxbow lake water show similar values (no statistical differences at $P<0.05$). However, in summer at the most remote vegetation-free sites, DO contents were lower, even by 1–2 mg O_2 L^{-1} (Fig. 3), when compared to downstream/upstream arms.

In lentic reservoirs, chlorophyll and turbidity may be co-indicators of groundwater recharge. They mainly depend on phytoplankton development, which is controlled by the oxygen and light conditions as well as nutrient content in the water. Within semi-lotic lakes, still connected at their downstream ends, longitudinal gradients of turbidity decreased with the distance to the main river, as a result of river backflow.

pH, electrical conductivity and suspended solids

Although all types of water bodies were circumneutral (pH = 6.1–8.2) and showed an average degree of mineralization, the oxbow lakes had the lowest values when expressed in both electrical conductivity (average SEC = 442 µS cm^{-1}) and concentrations of total dissolved solids (TDS = 0.303 g L^{-1}). A range of hydrochemical environments can be noticed across the studied flood plains. Some general trends emerged between hillslope and alluvial aquifers, represented by the transect of four piezometers near to a semi-closed oxbow in the Łyna River valley near Smolajny. In Fig. 4, significantly higher SEC values can be seen along the hillslope (p.12–p.14) which amounted on average to 600 µS cm^{-1} when compared to alluvial water (p.15) which directly influences the oxbow lake and the river (about 380 µS cm^{-1}).

Among the three types of oxbow lakes, the widest range in mineralization showed the lentic type. Similarly to other types of oxbow lakes, vertical profiles of specific conductivity had the highest values at the bottom. The near-bottom SEC values were very sensitive to the groundwater recharge. Based on the example of a lentic flood plain lake presented in Fig. 3, at its

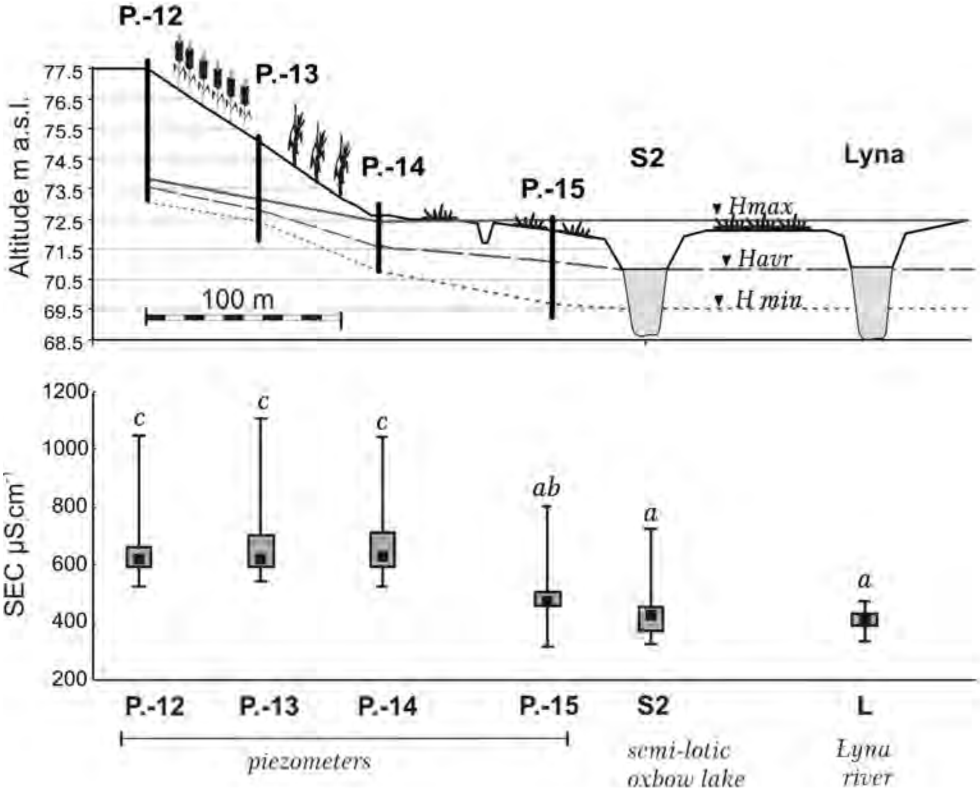

Fig. 4 Changes in water level across the Łyna River valley monitored in the transect of piezometers and semi-lotic oxbow lake S2 and the Łyna River at Smolajny. Lower chart illustrates distribution of changes in electrical conductivity in studied waters. Dots indicate median value, boxes 25 and 75 percentiles and whiskers minimal and maximal values. The same letters denote groups of homogeneous means (ANOVA), not different in Duncan's test at P<0.05.

most remote site from the river, where groundwater showed significantly elevated SEC values, we noted the increase in this parameter to 400 µS cm^{-1} when compared to 240 µS cm^{-1} at the downstream and 280 µS cm^{-1} at upstream arms. In light of the above, higher specific conductivity and lower pH values in closed oxbow lakes when compared to the river water could be good indicators of groundwater supply.

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. A progressively higher load of suspended solids, together with a decreasing organic content *vs* the increasing connectivity to the main channel, can be seen. Water bodies where the groundwater supply prevails (lentic) showed a very low suspended load while the channels bi-connected with the river showed markedly higher concentrations of suspended matter.

In the example of the Łyna River valley, every studied surface and groundwater environment shows its individual hydrochemical character (Fig. 5). The data set, which consisted of pH, DO, TDS and SEC values, allowed for clustering the aquatic environments. The river-dependant habitats were semi-open (S-O) and open (O) lakes. Closed (C) lakes and ditches dewatering the valley floor were closely related to alluvial waters while hillslope aquifers created a cluster of water in piezometers located along the valley slope (p.12–p.14).

Nutrient content

In the water of the studied oxbow lakes, the nutrient content of groundwater origin is superimposed by other factors dependant on the retention time of the water and nutrient uptake by primary producers. During relatively infrequent and short-term overflows we also noticed disrupted gradients in nutrient contents in oxbow lake water.

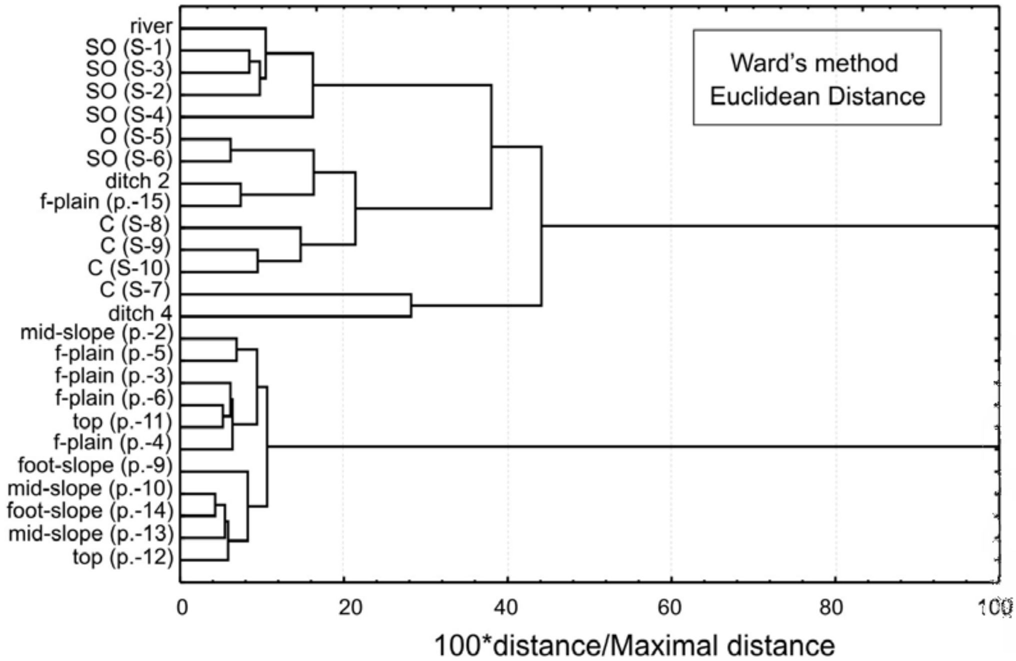

Fig. 5 Clustering tree diagram based on pH, TDS and SEC data set for the Łyna River valley (Ward's method, Euclidean distance).

Dissolved nutrient contents, here referred to as NO_3-N and NH_4-N in flood plain water bodies, generally increased with connectivity to the river. Within semi-open lakes we found distinct longitudinal gradients in nitrate- and ammonium-N resulted from the upstream groundwater supply mixing with the river backflow at the downstream end.

In terms of NO_3-N concentrations, oxbow lake water is not significantly different from the river or alluvial groundwater (Duncan test, $P<0.05$). Ammonium concentrations were statistically higher in closed oxbow lakes and also tended to increase with depth below the water surface. Advanced processes of eutrophication at reducing conditions are responsible for the statistically higher ammonium concentrations in this group of oxbow lakes.

The forms of mineral-N present in the alluvial and hillslope aquifers were related to indicators of the redox status of the aquifer (Fig. 4). These differences in reducing conditions were reflected in the distribution of the mineral-N species. Ammonium had the opposite pattern to NO_3-N, with concentrations generally increasing from the top to the foot of the slope (Fig. 2). The groundwater in hillslope aquifers in agriculturally used areas is nitrate-rich: it is three times higher at top- and mid-slope (1.23 and 1.32 mg N L^{-1}, respectively) than at foot-slope, alluvial aquifers or river water. Although alluvial aquifers provide relatively nutrient-poor water, low levels of NO_3-N in lentic water bodies also result from the biogeochemical processes and the nutrient uptake by plants.

PCA performed on physico-chemical parameters in the flood plain water bodies and environmental variables explained 59.08% of the variance in time (Fig. 6). All parameters involved in biochemical processes such 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 flood plain lake.

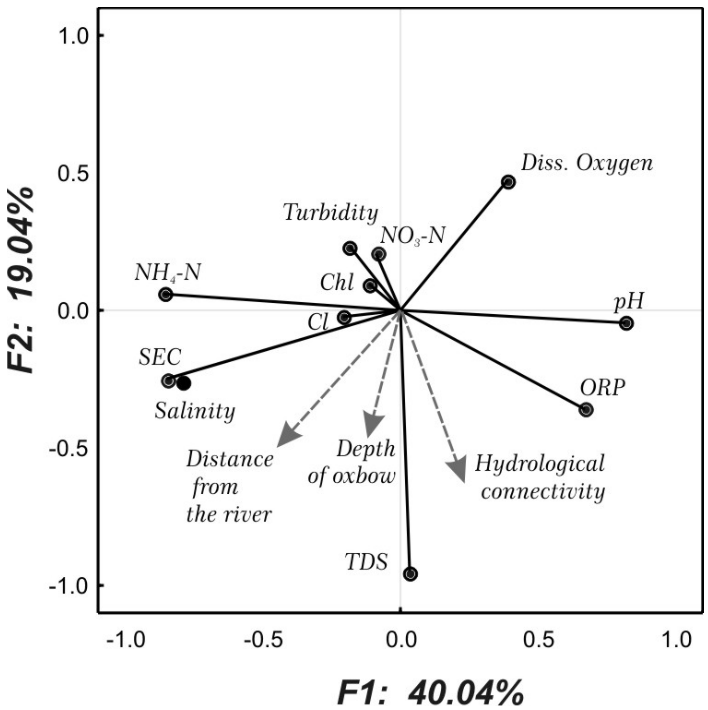

Fig. 6 Results of the principal component analysis (PCA) between environmental (nominal) variables and physico-chemical parameters of oxbow lake water.

CONCLUDING REMARKS

Considering the processes related to the lateral or vertical hydrological connectivity of flood plain lakes, we observed seasonal changes in physical and chemical properties of some ecosystems that function in postglacial river valleys in temperate climate zone in northern Poland. The amount of water the oxbow lake receives from each of these depends on the position of the wetland in respect to the surface topography and the groundwater table (Trémolières *et al.*, 1993; Tockner *et al.*, 1999) which are very often imposed by effluents from intensively agriculturally-managed reclaimed areas (Glińska-Lewczuk, 2005). For this reason, in spite of the close spatial arrangement along one flood plain, they may undergo different rates of dynamic changes, succession and evolution. The degree of connectivity with the parent channel is responsible for heterogeneity of the ecosystem productivity (Amoros, 2001; Amoros & Bornette, 2002) Lotic oxbow lakes are particularly open to exchange of matter with the river, which leads to higher concentrations of macroelements. Ecosystems isolated from the nearby river for most of the year acquire a lentic character that promotes autogenic, mainly organic, matter cycling. This results in changed macrophytes species composition, especially those adapted to anoxic conditions at the bottom, as well as decreased productivity of such ecosystems due to e.g. denitrification.

Nevertheless, high gradients of temperature, dissolved oxygen contents in some vertical profiles oxbow lakes indicate active exchange of ground and surface water. It is evidence that those water bodies must exist with a sufficient discharge potential of alluvial or hillslope aquifers. Therefore, such high gradients as presented in the paper meet the conditions listed by Amoros (2001): (i) a 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.

Those ecosystems, which do not show such gradients in the water column, could be deprived of groundwater supply as the result of blocking by fine sediment accumulation. In such reservoirs the eutrophication and subsequent terrestialization occurs at a faster rate (Bornette *et al.*, 1994).

The assessment of the direct influence of hillslope and alluvial aquifers on functioning of the oxbow lakes is obscured by numerous biogeochemical processes in aquatic environment. Dense plant cover also has a profound effect on water temperature and pH. In winter, under long-term ice cover, where no external aeration is possible, oxygen reserves are quickly utilized for respiration and decomposition and the oxygen deficits may only be increased by sub-oxidized groundwater. The close relation between hydrological conditions and the three oxbow lakes groups suggests that the clustering approach based on water chemistry data could be used for the assessment of groundwater recharge susceptibilities.

The share of riverine and groundwater water sources in supplying oxbow lakes is highly variable due to periodical flood pulses. In periods of high hydrological intensity, the water cycling within the valley is accelerated and oxbow lakes are fed primarily by river water. Soon after the flood, they slowly release the water back to the river (Galat *et al*., 1998). Afterwards, groundwater discharge to an oxbow lake dominates over the riverine and transforms properties of water in the lake. Our data on longitudinal gradients in physical parameters within the single loop of a flood plain lake confirm the results of Juget *et al*. (1979) on cut-off channels in the Rhone flood plain and of Klein *et al*. (1995) on the Rhine, who showed decreasing turbidity and suspended solids contents and explained it as a result of the mixing effect of upstream groundwater with river backflow at the downstream arm.

Our research confirmed the significance of groundwater for the ecological succession of oxbow lakes. The data demonstrated, that nutrient-poor alluvial groundwater may have a diluting effect on nutrient concentrations in flood plain ecosystems and could initiate regression from a highly eutrophic state to a mesotrophic state. When the oxbow lake is intensively supplied by nutrient-poor groundwater, its water tends to be more meso- or oligotrophic, like that also described by Piégay *et al.* (2001). Lower nutrient concentrations discharged to the flood plain lakes with alluvial groundwater may constrain the rate of eutrophication of a 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).

Acknowledgements This scientific study was financed by educational funds as research project no. N N305 170636.

REFERENCES

Amoros, C. (2001) The concept of habitat diversity between and within ecosystems applied to river side-arm restoration. *Environ. Manage.* **28**, 805–817.

Amoros, C. & Bornette, G. (2002) Connectivity and biocomplexity in waterbodies of river flood plains. *Freshwat. Biology* **47**, 517–539.

Bornette, G., Amoros, C. & Collilieux, G. (1994) Role of seepage supply in aquatic vegetation dynamics in former river channels: Prediction testing using a hydroelectric construction. *Environ. Manage.* **18**(2), 223–234.

Galat, D. L., Frederickson, L. H., Humburg, D. D., Bataille, K. J., Bodie, J. R. & Dohrenwend, J. (1998) Flooding to restore connectivity of regulated, large-river wetlands (Lower Missouri River). *BioScience* **48**, 721–733.

Glińska-Lewczuk, K. (2005) Oxbow lakes as biogeochemical filters for nutrient outflow from agricultural areas. In: *Dynamics and Biogeochemistry of River Corridors and Wetlands* (ed. by L. Heathwaite, B. Webb, D. Rosenberry, D. Weaver & M. Hayash), 55–69. IAHS Publ. 294. IAHS Press, Wallingford, UK.

Glińska-Lewczuk, K. (2009) Water quality dynamics of oxbow lakes in young-glacial landscape of NE Poland in relation to their hydrological connectivity. *Ecol. Engng* **35**, 25–37.

Juget, J., Yi, B. J., Roux, C., Richoux, P., Richardot-Coulet, M., Reygrobellet, J. L. & Amoros, C. (1979) Structure et fonctionnement des écosystèmes du Haut-Rhone français. VII. Le complexe hydrographique de la lône des Pêcheurs (un ancient méandre du Rhône). *Schweizerische Zeitschrift fűr Hydrologie* **41**, 395–417.

Klein, J. P., Robach, F., Vanderpoorten, A. & Trémolières, M. (1995) Spatio-temporal aquatic vegetation patterns in former channels in relation to their isolation from the River Rhine (eastern France). *Acta Botanica Gallica* **142**, 601–616.

Kondolf, G. M., Boulton, A. J., O'Daniel, S., Poole, G. C., Rahel, F. J., Stanley, E. H., Wohl, E., Bång, A., Carlstrom, J., Cristoni, C., Huber, H., Koljonen, S., Louhi, P. & Nakamura, K. (2006), Process-based ecological river restoration: visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. *Ecol. & Society* **11**(2), 5 http://www.ecologyandsociety.org/vol11/iss2/art5/.

Petts, G. E. (1990) The role of ecotones in aquatic landscape management. In: *The Ecology and Management of Aquatic-Terrestrial Ecotones* (ed. by R. J. Naiman & H. Décamps), 227–261. Man and the Biosphere Series 4, UNESCO, Paris. The Parthenon Publishing Group, Carnforth, UK.

Piégay, H., Bornette, G. & Grante, P. (2001) Assessment of silting-up dynamics of eleven cut-off channel plugs on a free-meandering river (the Ain River, France). In: *Applied Geomorphology, Theories, and Practice*. John Wiley & Sons, New York, USA.

Swanson, F. J., Gregory, J. R., Sedell, J. R. & Campbell, A. G. (1982). Land-water interactions: the riparian zone. In: *Analysis of Coniferous Forest Ecosystems in the Western US* (ed. by R. Edmunds), 267–291. Academic Press, New York, USA.

ter Braak, C. J. F. (1995) Ordination. In: *Data Analyses in Community and Landscape Ecology* (ed. by R. G. H. Jongman, C. J. F. Ter Braak & O. F. R. Van Tongeren), 91–173. Cambridge University Press, Cambridge, UK.

ter Braak, C. J. F. & Smilauer, P. (2002) Canoco for Windows 4.5. Biometrics, The Netherlands.

Tockner, K., Pennetzdorfer, D., Reiner, N., Schiemer, F. & Ward, J. V. (1999) Hydrological connectivity and the exchange of organic matter and nutrients in a dynamic river-flood plain system (Danube, Austria). *Freshwat. Biol.* **41**, 521–535.

Tockner, K., Stanford, J. A. (2002) Riverine flood plains: Present state and future trends. *Environ. Conserv.* **293**, 308–330.

Trémolières, M., Eglin, I., Roeck, U. & Carbiener, R. (1993) The exchange process between river and groundwater on the Central Alsace flood plain (Eastern France). *Hydrobiologia* **254**, 133–148.

Ward, J. V. (1989) The four-dimensional nature of the lotic ecosystem. *J. North American Benthological Soc.* **8**, 2–8.