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RIVER-LAKE SYSTEM IN A MOSAIC LANDSCAPE; MAIN RESULTS AND SOME IMPLICATIONS FOR THEORY AND PRACTICE FROM STUDIES ON THE RIVER JORKA SYSTEM (MASURIAN LAKELAND, POLAND)

ABSTRACT: The basic results and conclusions of multi-year studies (described in detail in previous papers) on the river-lake system in the lakeland region of north-eastern Poland are shortly presented in relation to the selected general ecological problems. The study area was proved to be representative of the mosaic landscape structure and of the river-lake system as a trophic continuum with the spatial pattern of human impact established a century ago. Generally low export rates of nutrients and relatively low input to the lakes were found as typical of the region. However, year-to-year variation in nutrient export from the lake watersheds was high, mostly related to the discharge variation, and highest in the vernal period; the highest values were found for polluted fragments of the watershed.

The long-term relative stability of in-lake trophic conditions was found and their basic relation to the lake position in the river system. The role of wetlands (isolated patches and the zones close to lakes) in diminishing the nutrient input was proved and their vegetation was described. Some consequences of the possible global warming and decrease in discharge and water table in the region were pointed out, such as the pulsing (concentrated in the freshet period) system of water and nutrient supplying, *sink* or *source* function of lakes in the river system (positive or negative nutrient retention in successive lakes), change in eutrophication rate, and its symptoms. The main implications for watershed management in the lakeland region are indicated.

KEY WORDS: river-lake systems, landscape and catchment studies

1 . THE RIVER JORKA SYSTEM AS AN AREA REPRESENTATIVE OF POSTGLACIAL LANDSCAPE

The study of the Jorka river-lake system in the Masurian Lakeland, conducted during 1978–1998 and presented in this volume, shows that this is a typical system representing a hilly postglacial landscape located in north-eastern Poland, and contributing to 20% of the area of Poland. Characteristic hydrographic systems of landscapes of this kind are formed by rivers or streams connecting lakes or flowing through lakes, mainly shallow and small, and also by larger systems of trough-like lakes (Photo 1) (Fig. 1 in Hillbricht-Ilkowska 2002a).

Diversified relief (hills, plains, land depressions, valleys) combined with agricultural-forest land use produce a mosaic structure of natural environment that was analysed, among others, by using aerial photographs (1:10 000). The number of landscape patches (as defined by Forman and Godron 1986), that is, areas with a relatively homogeneous cover and use (arable fields, pastures, meadows, wetlands, forests and afforestations) varies from a few to more than 10 per km^2, and their surface area varies from several to more than 10 ha. At such a high dispersion of mainly small landscape patches, the ecotones, that is, zones of contact or transition zones between different patches are very long, up to several km km^{-2} (Rybak 2002 a, b).

Next to lakes and streams, wetlands occurring in land depressions without outflow, along lake shores and in stream valleys are ecosystems of particular importance in the lakeland landscape. Although they cover a small part of the catchment basin (no more than 15%), they perform an important role in the landscape due to their high dispersion (up to 20 per km^2) and continuous occurrence in close vicinity to water bodies. In particular, they function as barriers in processes of matter transport and transformations, and they increase the biological and site diversity of natural environment (Haycock *et al.* 1997, Mitsch *et al.* 2000).

These aspects of the structure and function of the lakeland landscape, including lake ecosystems and wetlands as its components, were the subject of the study as exemplified by a small catchment (about 60 km^2) of the Jorka river, the Masurian Lakeland, flowing through several lakes, and subjected to agricultural-forest management (Fig. 1 in Rybak 2002a). This paper sums up the most important findings of different long-term studies presented in individual papers, and it also discusses some general patterns and implications for conservation.

2. JORKA RIVER SYSTEM AS A CONTINUUM

Relatively natural and undisturbed hydrographic system is characterized by a continuous, directional changes of many factors, starting with headwaters to the mouth, as stated in the *river continuum concept* (Cushing *et al.* 1995). Consequently, some properties of lakes connected by running waters can differ in a predictable way, depending on their location in the basin. Soranno *et al.* (1999) and Kratz *et al.* (1997) showed this for several lake systems in North America. This was also the case of several systems in the Masurian Lakeland (Hillbricht-Ilkowska 1999a). The Jorka catchment and the lakes on the river are examples of an integrated system with a clear directional spatial variation in water fertility, lake productivity, and human impact. In general, this is expressed as a directional increase in trophic resources of water, ranging from mesotrophic in the upper part of the catchment basin to heavily eutrophic in the lower part (Fig. 1 in Hillbricht-Ilkowska 2002a and Rybak 2002a). This relatively natural direction, obvious in undisturbed regions, is reinforced by the spatial distribution of human impact that has been continued for several hundred years (Photo 2), with prevalence of farmland in the lower and middle parts of the basin and forests or pastures in the upper part. This implies also that, in general, systems of high and moderate removal potential (swamp forests, wetlands, wet meadows) are better represented in the upper catchment (50–80% cover) than in the lower (10–20% cover) (Rybak 2002a).

As a result of this spatial variation in the catchment, the following water properties show an increasing trend: electrolytic conductivity and concentration of chlorides in lake effluents and in lake waters from below 350 to more than 500 μS cm^{-1} and from below 15 to more than 30 mg l^{-1} for upper and lower parts of the basin, respectively. A similar direction of variation was observed for the annual input (from all sources) of phosphorus and nitrogen in grams per m^2 of lake surface; it varied from less than 0.1 to more than 1 (2) for phosphorus and from less than 2 to more than 10 (50) for nitrogen in upper and lower lakes, respectively. Also the N:P ratio of the load increased from over the Redfield ratio (20–30) for upper lakes to below the Redfield ratio (less than 20) for lower lakes. With location of the lake down the river, the contribution of the river input to the load increased, whereas the contribution of precipitation decreased, as well as the contribution of waters polluted with municipal waste waters and agriculture increased. Finally, typical indices of productivity in lakes, such as the mean annual water transparency, chlorophyll content and algal biomass show a similar direction of variation between the highest lake and the lakes located in the middle and lower parts of the catchment (Hillbricht-Ilkowska 2002b, c, Rybak 2002b).

3. NUTRIENT TRANSPORT IN THE JORKA RIVER SYSTEM AND THE ROLE OF WETLANDS

In general, the annual export of nutrients from 1 ha of the Jorka catchment was lower than from other agricultural landscapes covering a similar area. This conclusion is based on estimates of the annual export of nutrients from more than 10 small lake shore catchments drained by shallow streams, and monitored for several-year periods. The annual export of total phosphorus from these catchments was typically less than 0.5 kg ha^{-1}, that of organic nitrogen, including ammonia nitrogen, below 10–15, and nitrate nitrogen below 2 kg ha^{-1}. These values can be considered as concerning non-point surface runoff in the lakeland landscape under study subjected to a moderate agricultural use. In some cases when draining waters received municipal sewage (e.g. areas of wastes dumping) the respective values of the export could reach 5, 60, and 4 kg ha^{-1} for TP, TKN and NO_3^-, respectively, but these values should be considered as concerning the runoff dominated by point sources. It should be noted that the runoff of nitrate nitrogen was very low as compared with that in similar regions subjected to intensive farming where it was several times or even more than 10 times higher. This may be a property of the lakeland landscape where various kinds of wetlands, thus habitats characterized by the highest nitrogen removal potential, are abundantly represented, and agricultural land use is moderate and limited by the relief and soil fertility (Rybak 2002b).

A characteristic feature of the landscape under study is seasonal dynamics of nutrient export from the catchment and dependence of this export on annual changes in discharge. Typically, over half of the annual export from the monitored catchments (and loading to lakes with river waters) occurs during the spring freshet period, that is, during a short period April–May. Both the export from and the input to lakes in the remaining periods are largely reduced or even non-existent. Moreover, the value of export is more dependent on variation in discharge than on variation in nutrient concentration in surface runoff. This implies that the functioning of the catchment as a source of matter is more closely related with hydrology than with land use in this region, excluding the cases of heavy soil pollution with sewage (Rybak 2002b).

The functioning of a typical river-lake catchment can be compared to a specific *pulsing system* in which a complete hydrological and geochemical connectivity among the components exists most often during several-month spring periods, whereas in the remaining periods of the year it varies in unpredictable way, and frequently the system is hydrologically disrupted or it functions occasionally. This situation reminds us of the functioning of flooded river valleys or riparian zones, for which the term *pulsing systems* was coined by Junk (1997). This situation seems to be reinforced by possible climate change (see below).

The described hydrological variation in the catchment basin determines, most of all, the functioning of wetlands both dispersed in the form of patches and in the lake shore zone.

In total, 26 plant communities were described in wet habitats bordering lakes and the Jorka river. This vegetation forms a disrupted belt (occupying, about 60% of the shore line of the lakes and the river), from several to several hundred metres wide, merging into the littoral zone of the lakes. Typically, these are alder swamps (Photo. 3) forming a characteristic component of the lakeland landscape, most often adjacent to crop fields, managed meadows or pastures on one side and to aquatic vegetation of the lake littoral on the other side. In the contact zone between wetland vegetation and crops, there exists a zone of nitrophilous vegetation (with *Urtica dioica*). In the study area, the wetland vegetation is largely transformed and destroyed (along 20–70% of the shore line) as a consequence of forest clearing, cattle grazing, or waste/garbage dumping. Moderately transformed are small mid-field wetland patches (2.5–0.7 ha) scattered in the landscape at a density of about 20 km^{-2}, often without surface outflow or with a seasonal outflow. In these habitats, 22 plant communities have been described. These are mostly reed beds and shrubbery in meadows, at least half of them being managed. As many as 1/3 of the total number of wetlands under study were degraded (overdrying, garbage disposal). Together with managed wetlands, the heavily man-transformed plant communities accounted for about 41% of the wetlands. The remaining wetlands (more than half) were covered with natural or little transformed permanent vegetation of a high density (Kloss and Wilpiszewska, 2002, Wilpiszewska and Kloss 2002).

The wet zone about 30 m wide, bordering on the lake littoral seems to be sufficient for effective nutrient removal from the surface and ground runoff. It was found that nutrient concentrations in this zone did not exceed 3 mg l^{-1} of nitrate nitrogen, 0.7 mg l^{-1} of dissolved phosphorus, and 4 mg l^{-1} of dissolved organic nitrogen (with ammonium nitrogen). The most frequent values of nitrate nitrogen were not higher than 1 mg l^{-1}, confirming the generally low concentrations of this chemical in the landscape under study. Within this zone, its concentration declined from 20% of the initial concentration to 90%. The most rapid decline occurred within the first 5–7 m from the edge of a crop field or pasture across the wetland separating farmland from the lake. For nitrate nitrogen, the rate of decline increased with the initial concentration. This implies that denitrification was responsible for nitrogen removal and that this process might have been limited by the availability of nitrates. The efficiency of the barrier function of the wetland zone along lake shores depends on the content of water in the soil which, in turn, depends on the rate of water runoff. Hence, the highest decrease in nitrates was observed in spring, when their input with waters was the highest. Decreases in the concentration of other nutrients were more variable and unpredictable, but a strong tendency to reduction of the concentration of phosphorus dissolved in waters crossing the zone of wetlands was observed (Rzepecki 2002).

Experiments with cores of wetland soils confirmed that the reduction of nitrate nitrogen (denitrification) was most enhanced by low redox potential (anaerobic conditions), typically associated with the saturation of soil with water, though under these conditions, dissolved phosphorus and ammonium nitrogen are released. In turn, the redox potential typically associated with lower water content in soil (aerobic conditions) promotes the sorption of phosphorus and release of nitrate nitrogen from organic nitrogen (nitrification) (Rzepecki 2002).

The results of field studies show that the observed dynamics of nutrient concentration in waters of wetlands depends on many factors. The basic reason seems to be the system of water runoff that is variable in time and range, also the saturation of soil and wet habitats with water, especially beyond the spring period. In the spring and summer periods, especially in dry years, the spatial system of surface and ground water runoff becomes discontinuous and seems to loose its connectivity. Even occasional rainstorms cannot regenerate the system sufficiently to enable permanent functioning of small streams, as well as wetland patches and zones. The lowering of water table and climatic changes in recent years seem to reinforce this phenomenon. However, the present state of plant cover in wetland patches and lake shore zones in the fragment of the lakeland under study seems to be relatively good, as about half of them support complex and dense plant communities that can function as barriers when water is not deficient.

Nutrient removal potential of lake shore ecotones in the study landscape is comparable to that of riparian habitats along rivers (Haycock *et al.* 1997, Mitsch *et al.* 2000).

4. LAKE EUTROPHICATION IN MOSAIC POSTGLACIAL LANDSCAPE

Long-term studies (1970s *versus* 1990s) on trophic conditions in five lakes of the Jorka catchment basin, as indicated by a few typical indices such as water transparency, phosphorus concentration, chlorophyll concentration, phytoplankton biomass, and oxygen deficiency in hypolimnion during the spring and summer periods, did not show trends indicative of a progressive eutrophication of all parts (upper and lower) of the basin. Annual variation in all indices was high but not directional, whereas permanent differences were maintained among the mesotrophic lake in the headwater part of the basin, eutrophic lakes in the middle part, and heavily eutrophic lake in the lower part. This situation resulted, among other things, from spatial diversification of the catchment in terms of agricultural impact, and due to this, these lakes formed a spatial continuum as described above. A moderate or strong correlations were found between such trophic parameters as algal biomass, water transparency, and chlorophyll content in both the summer and spring periods. These correlations are similar to those found in other groups of Mazurian lakes. Like in other lakes, no indication was found that phosphorus concentration is a good predictor of the trophic state of a lake because of its high variability, the values of its concentration being of "instantaneous" character, and because of the absence of correlation with other trophic parameters of the lake (Hillbricht-Ilkowska 2002c).

The catchment and lakes under study are supplied mainly with stream waters, waters from direct catchment and precipitation (that is with areal surface runoff) and to a lesser extent with direct sewage discharge from the catchment fragments affected by sewage and garbage. This implies that in a mosaic landscape with widely scattered habitat patches that differ in barrier potential and with moderate and dispersed agriculture, the quality of lakes can be maintained at a relatively stable and natural level depending on the location in the catchment and on morphometric conditions if point sources of sewage are absent. The susceptibility of a system to this type of loading can be illustrated by Lake Głębokie, located in the middle part of the catchment. After the cessation of a trout culture (run over 10 years), water transparency increased in the lake, whereas the concentration of chlorophyll and algal biomass decreased. The lake returned to the state of meso-eutrophic conditions, or to weak eutrophic conditions appropriate for its depth and location in the catchment (Hillbricht-Ilkowska 2002c).

The only directional change observed in eutrophic lakes of the Jorka basin was the replacement of cyanobacteria that dominated in the 1970s by dinoflagellates that dominated in the 1990s (Jasser in Hillbricht-Ilkowska 2002c). This switch may be due to the reduced load of nutrients from the catchment and to seasonal export of these nutrients from internal sources, as described below. This is a positive process from the viewpoint of eutrophication, and it can be expected that changes in the hydrological regime of the catchment in a mosaic landscape can lead not only to a relative stability of trophic resources but also to their seasonal decline, and consequently to changes in the group composition of the phytoplankton (Hillbricht-Ilkowska 2002b, c).

Trophic resources of the lakes in the landscape under study were mainly determined by spring high waters as the values of nutrient export from the catchment and lake loading were the highest in this period of the annual cycle. Consequently, the load and retention of nitrogen and phosphorus in lakes were characterised by strong seasonality, as well as the stability and mobility of waters were strongly seasonal – the highest hydraulic loading of lakes and the highest intensity of water exchange due to heavy throughflow occurred in that period. For this period, a strong correlation was found between the load of phosphorus in lakes and its concentration in lake waters, which was not observed in the remaining seasons of the year. Beyond spring periods, the input, load, and retention of these nutrients in lakes were lower (especially for nitrogen), and they became particularly low in the summer periods of the late 1990s. A direct reason was a clear reduction of flow in the surface network of the system (a possible effect of climate change – see below). The river-lake system and its hydrological-biogeochemical functioning approached pulsing systems (Junk 1997), in which wetlands, shore zones, and trophic resources are renewed during the short spring period of each year. These dynamics seems to be reinforced by present climate changes (increase in temperature, evaporation, and in frequency of extreme events) and by total decrease in water table observed over vast areas of the lowland (Hillbricht-Ilkowska 2002c).

5. POSSIBLE EFFECTS OF CLIMATE CHANGE IN THE RIVER JORKA CATCHMENT

Close to 20 years study conducted in the catchment and lakes of the river Jorka system revealed changes in their functioning that can be related with climate variation in successive years. This is the case of the increased and positive values of the index of North-Atlantic Oscillation which is correlated with higher temperatures in winter and spring, both mean and maximum, tendency to high mean and/or maximum temperatures in summer, reduced or more irregular precipitation, increased evaporation, also more frequent and prolonged droughts. The years 1997/1998 are among warm and dry, with particularly low discharge and the whole period of intensive study during 1996–1998 differed in this respect from the study period in the late 1970s (Hillbricht-Ilkowska 2002a).

After the spring and early-summer periods, when the discharge reached the highest values and the hydrographic system was continuous, many surface streams disappeared in the study periods mentioned above, and short-time hydrological isolations of different parts of the river system were frequent in the summer and autumn. The lake water became less mobile and the lakes became less throughflowing. The input of nutrients to the lake surface decreased in the annual cycle (April–October) and also in the summer period, especially in 1997/98. This decrease was more pronounced for nitrogen than for phosphorus, hence the N:P ratio in the input to a lake clearly dropped. The decreasing input of nutrients from the catchment and decreasing water mobility was combined with growing intensity of internal loading, that is, with the increasing rate of nutrient release from bottom sediments. As a result, temporary stronger outflows from lakes can carry a load exceeding the external loading. Under these conditions (decreasing flow-decreasing external loading-increasing internal loading-temporarily increasing outflow), the net retention of nutrients from external sources declined in the system. Consequently, the lake temporarily switched from the *sink* system to the *source* system. This was especially the case of the lakes located in the lowest reaches of the river, where trophic resources retended in bottom sediments were greatest from the historical perspective. Negative retention for annual values for 1997– 1998 years was noted for total phosphorus and, to a higher extent, for organic nitrogen. The net retention of nitrate nitrogen in successive years showed high positive values in each of the study years. It seems that the removal rate of this nutrient in lakes was mostly a result of effective denitrification enhanced by anaerobic conditions in sediments and in hypolimnion, along with their saturation with organic matter (Hillbricht-Ilkowska 2002c).

The system of five lakes on the river Jorka seems to be a good indicator of possible climate change, so called global warming. An increase in air temperature, thus increased evaporation and irregular precipitation, can markedly disturb hydrological functioning of the catchment not only in terms of the disappearance of ecotonal wet habitats but also because of the disruption of biogeochemical relationships between the catchment and the lakes. Consequences of these changes for the evolution of lakes and their eutrophication are not fully recognised, especially with respect to shallow and moderately deep lakes connected by a river in the mosaic landscape subjected to moderate human impact. It is possible that some consequences can temporarily limit symptoms of eutrophication, but we should agree with Schindler (1997) that long-term predictions contain many unknowns.

6. SOME DIRECTIONS OF THE PROTECTION AND MANAGEMENT OF THE LAKELAND LANDSCAPE AS IMPLIED BY THE RESULTS OBTAINED FOR THE JORKA CATCHMENT

The Jorka catchment is situated in north-eastern region of the lakeland and it forms a part of so-called Green Lungs of Poland (Wolfram 2000). In the plan for spatial development of Poland, the priority goal for this region is recreation and tourism, thus the maintenance of the natural value of the land and a high quality of running waters and lakes. The same priorities refer to agriculture (moderate use of fertilisers, abundant ecological and agrotouristic farms), industry (no heavy industry and mining), and to public utilities (sewage treatment).

The study of the Jorka river catchment and lakes revealed some phenomena and processes critical to the implementation of this objective.

Wetland patches of various kinds are of key importance for environment and, thus, biological diversity of the region. This is especially the case of small patches of 0.5–1 ha, the number of which can be more than ten per km^2. A similar barrier function, reducing pollution and runoff from agricultural land, is performed by wetlands bordering lakes and forming a continuous zone comparable to riparian zones along river beds. These habitats are threatened because of drainage and drying, probably reinforced by the lowering of water table over large areas and by climate warming. There is an urgent need for their inventory and protection as so-called *ecologically useful land patches* in order to prevent them from converting into garbage dumps and ploughing, or from other kinds of destruction. Similarly, the protection of the shoreline zone from clear cutting, cattle grazing, and converting into fertilised and managed meadows or pastures is necessary to maintain their continuity and appropriate width. Their active restoration may also be needed to fill gaps with the vegetation corresponding to edaphic conditions.

Also some regulation of runoff from the catchment may be needed to ensure a prolonged wetness of the isolated fragments of wet habitats, and to lengthen streams crossing farmland by restoring natural meanders, or the like. These are well known treatments, applied in rivers, streams, and their floodplains (Boon *et al.* 1992, Hillbricht-Ilkowska 1999b).

The so-called *watershed approach* to the management of waters and the natural environment is commonly recognised and even required by the Water Directive of the European Union (2000), and also proposed as one of several priority ecological problems in Poland (Andrzejewski 2002). This idea lies at the basis of the International Network of Basin Organisations (2002). The study of the fragment of the lakeland landscape in the Jorka catchment provides the basic material that can be used for making spatial plans for various lakelands.

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