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NUTRIENT LOADING AND RETENTION IN LAKES OF THE JORKA RIVER SYSTEM (MASURIAN LAKELAND, POLAND): SEASONAL AND LONG-TERM VARIATION

ABSTRACT: The nutrient (TP, $N\text{-}NO_3$, TKN – Kjeldhal nitrogen) loading to lakes (from river, precipitation, direct catchment) and in-lake retention were calculated for five successive lakes of the river-lake system typical of the mosaic, hilly lakeland region (the Jorka system, Masurian Lakeland). The annual values of loading for TP and TN were mostly not higher than 1.0 and 15.0 g m^{-2} lake area, respectively and rather low compared to other river-lake systems in the lakeland region. However, these values as well as nutrient in-lake retention decreased in 1997–1998 (warm and dry years) compared with 1978 and 1996, together with the decrease in discharge and exchange rate of lake water. In selected cases the retention of TP and TKN became negative which means that the lake functioned as the source of nutrients for downstream fragments of the system. The retention of nitrate-nitrogen was usually positive – lakes remained effective sites for its removal (denitrification). The possible changes in functioning of small catchments and chains of shallow, eutrophic lakes under the conditions of global warming are discussed.

KEY WORDS: Nutrient loading and retention, lake chains, long-term studies

1. INTRODUCTION

In a typical lakeland landscape developed more than 13 thousand years ago, lakes are not isolated water bodies but parts of hydrographic systems, in which successive lakes are connected by shorter or longer sections of surface running waters such as streams, rivers, and ditches and/or groundwaters. Frequently these are distinct chains of lakes connected by running waters, commonly termed *lake chains* in landscape ecology (Soranno *et al* 1999, Tenhunen *et al.* 2001). Many physical, chemical, or biological characteristics of lakes can be ascribed to the position of a lake in such a landscape system (Kratz *et al.* 1997, Soranno *et al.* 1999). This approach was also adopted in the study of lake chains in the Masurian Lakeland, where they were termed *river-lake systems* to emphasize a functional relationship between the river and the lake (Hillbricht-Ilkowska and Bajkiewicz-Grabowska 1991, Hillbricht-Ilkowska 1993, 1999a, b). A distinctive feature of the river-lake system is the occurrence of directional changes in some chemical components of water and sediments in successive lakes starting with the headwater lake of highest position in the system to the lowest one. It has been found, for example, that the concentration of biologically inactive chemicals such as compounds of calcium, chlorine, magnesium, sodium, sulphur, or alkalinity, derived from weathering or from point sources, decreases in successive lakes of the system (Kratz *et al.* 1997, Soranno *et al.* 1999). This may also be the case of active chemicals but derived from a specified point source (sewage), as noted in the system of River Krutynia lakes on Masurian Lakeland (Hillbricht-Ilkowska and Bajkiewicz-Grabowska 1991). In contrast, biologically active compounds (phosphorus, nitrogen, organic matter) are more variable in the system, although generally concentration of these trophic compounds increases in successive lakes, and typically the lowest lakes are strongly eutrophicated (Soranno *et al.* 1999).

Variation in nutrient concentration in such systems is influenced by the fact that each successive lake receives matter and nutrients directly from its catchment basin (surface runoff, subsurface inflow, various small streams, sewage) as well as from the lake situated higher and the river section connecting these lakes and also from precipitation. These compounds are sedimented and then stored (permanently or periodically) in bottom sediments and vegetation, or they undergo various biotic transformations in processes of growth, excretion, decomposition and assimilation. At the same time, a part of the lake resources is transported downstream to systems situated lower. From the perspective of landscape biogeochemistry, such a lake system represents a landscape system in which successive ecosystems (lakes) differ with respect to the input and output of matter and, consequently, in the retention of a specified compound or nutrient. Soranno *et al.* (1999) and Hillbricht-Ilkowska (1999b) compare river-lake systems to a river system subjected to continuous changes conforming to the concept of *river continuum* (Vannotte *et al.* 1980) with irregularly located "inserts" (Ward and Stanford 1983), that is, successive lakes.

Typically, retention is estimated from external budget (see below), on the assumption that the input of matter with groundwaters is rather low for most lakes (especially shallow, 10–20 m deep), much lower than with surface waters. Positive retention means a net accumulation in a lake, and negative retention means a net export of a chemical downstream, from the lake. Net retention was estimated for more than ten lakes of the Krutynia river, (Masurian Lakeland), and for almost 20 lakes forming short chains in the Suwalski Landscape Park, North-eastern Poland (Hillbricht-Ilkowska 1993, 1994, Hillbricht-Ilkowska and Kostrzewska-Szlakowska 1996). Monthly values of the retention of different chemicals, for example, total phosphorus (TP) can differ from lake to lake of a river-lake system. Generally, they are positive and moderately high (up to 60% of the input load). But in some situations, the lake can export this chemical, for example, in summer, when the release of phosphorus from bottom sediments under anaerobic conditions outweighs the external input of this nutrient; then, retention can be negative, and even to 100% of the input. Noges and Jarvet (1998) and Noges et al. (1998) estimated that the retention of total nitrogen in a large, shallow lake accounted for almost half of its input with river waters (the main source of input to this lake), the retention of TP equalled to one third of the input, and the retention of $N\text{-}NO_3$ amounted to as many as 80% of the input. Hakala (1998) found that the retention of different dissolved forms of nitrogen ranged from 7 to 52% in different years and different lakes, and the retention of different dissolved forms of phosphorus varied from 71 to 92%. In other studies (Ahlgren *et al.* 1994, Ekholm *et al.* 1997), percentage retention of nitrogen and phosphorus largely differed, but was highest for nitrate nitrogen. This shows that denitrification, mainly in sediments, is responsible for an effective removal of the nitrogen supplied from external sources in the form of nitrates.

These results show that nutrient retention in lakes largely varies, and annual or monthly values are site-specific, depending on the kind, rate, and seasonality of input from all sources (river, precipitation, surface runoff, point sources like sewage) as well as on water retention in lakes. For the river-connected lakes, retention can also depend on the location of a lake in the lake chain system.

The results of this study are a part of a larger research programme focused on long-term changes in the functioning of the catchment basin of a lake chain typical of a hilly lakeland landscape where farming, forestry, and tourism are developed such as Masurian Lakeland (North-eastern Poland). The effects of catchment functioning on the condition of lakes were also studied (Hillbricht-Ilkowska 2002a). The objectives of the present paper concern:

- Estimates of nutrient loadings – total and from different sources separately, in successive years over 1996–1998 compared with those estimated in the late1970s (based on the data published in Hillbricht-Ilkowska and Ławacz 1983, Hillbricht-Ilkowska *et al.* 1983, Ławacz 1985).
- Estimates of the annual nutrient retention in the same periods and for successive lakes, and analysis of possible directional space-related changes, that is, referring to the location of a lake in the catchment, as well as to the multi-year and seasonal changes in discharge and precipitation.

2. STUDY AREA

The River Jorka (total lenght about 20 km) hydrographical system (Fig. 1) belongs to a small catchment (around 65 km^2) typical of the postglacial region of Masurian Lakeland. Its geographical location is 53° 45' N and 21° 25' E. The river flows through five lakes which form a gradient from deep (max. depth 16.4 m.) and large (174 ha) mesotrophic lake located upstream (recently bifurcated position) (Lake Majcz) with low exchange rate of water (several years) to small (41 ha) and shallow (max. depth 11.6 m.) eutrophic and polluted (willage waste waters) lake (Lake Jorzec) having high exchange rate of water (several months). The morphometric characters of the whole chain of lakes are given in Hillbricht-Ilkowska 2002a). The catchment of successive lakes and human impact form a sort of longitudinal gradient from low human impact in the upper

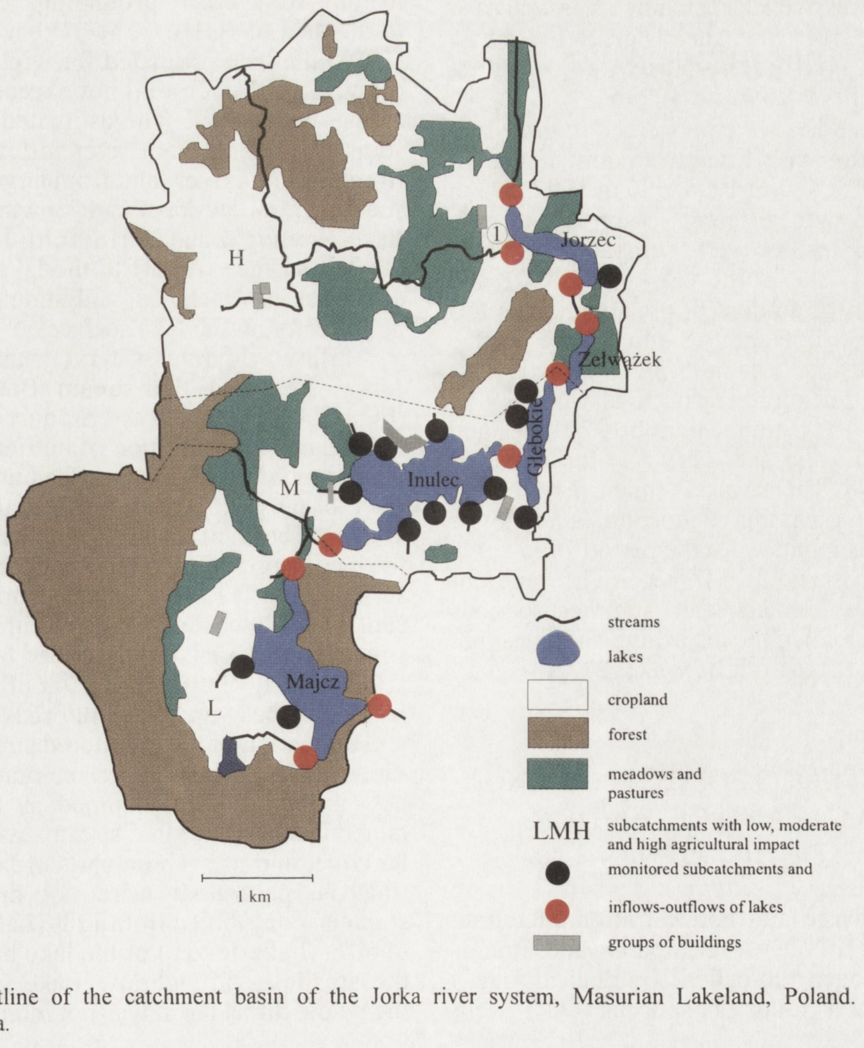

Fig. 1. Outline of the catchment basin of the Jorka river system, Masurian Lakeland, Poland. 1 – stream Baranowska.

part of the watershed (covered with forest) to the arable fields and settlement grounds (high human impact) dominating in the downstream section of the river watershed (Fig. 1).The area used for agriculture ranged from 16% in the upper part to 67% in the downstream section. The areal of pastures and grasslands is rather high in the whole watershed (28%). However, the average field plot is not larger than several ha (Hillbricht-Ilkowska 1999b), there are many small isolated potholes (wetland patches) as well as the wetland zone close to lake shore is more or less continual along the shores of the most lakes (Wilpiszewska and Kloss 2002). The number of residents is not higher than 2000 persons over the whole area as well as the amount of used fertilisers is not higher than 80 NPK per ha. The touristic impact is very modest and dispersed and the agritouristic type of tourism is promoted. The full description of the land cover and management of the successive lake catchments as well as of the whole river watershed is given in Rybak 2002a, Hillbricht-Ilkowska 2002a, Hillbricht-Ilkowska 1999b.

The studies were performed in three successive years with different amount of precipitation (mm): 463 in 1996, 596 in 1997, 593 in 1998, and with different seasonality in each year. The results were compared with the analogical data for the years 1977, 1978 and 1979 with the amount of precipitation as following: 636, 666 and 518 mm. The respective periods differed also in the average and maximal air temperatures respectively: 6.3–6.9° C and 9.6–10.5° C for the period 1977–1979 and 6.0–7.6° C and 9.8–11.2° C. for a period 1996–1998. There was a tendency for higher average and maximal temperatures and lower annual precipitation for the period 1996–1998 in comparison with 1977–1979. The same tendency was noted for summer periods (June–August) of the respective three-year periods (Hillbricht-Ilkowska 2002a).

3. METHODS FOR ESTIMATING LOADS AND RETENTION OF NUTRIENTS

Discharge and concentration of nitrate nitrogen (N-NO_3) total organic and ammonium nitrogen (so-called Kjeldhal nitrogen) (TKN), and total phosphorus (TP) were measured in inflows to and outflows from the lakes of the Jorka river and its tributaries at over ten sites (Fig. 1). Load estimates carried by small streams draining small lake subcatchment basins were used by Rybak (2000, 2002b) for estimating a unit export of nutrients from 1ha of direct catchment basin of the lake. The methods used to assess discharge and concentration of nutrients in lake shore streams and in inflows and outflows of the river to and from successive lakes are described in Rybak (2002b).

The loads of TP, TKN, and N-NO_3 (also TN as the sum of TKN and N-NO_3) were estimated for successive months from April through October of 1996, 1997, and 1998, and for all these months combined to get annual estimates. It was assumed that the estimates obtained for these seven months are close to real annual values, as they cover critical periods (spring flood, summer and autumn maxima of precipitation) for nutrient loading from lake surroundings. According to the data of Hillbricht-Ilkowska *et al.* (1983) the load estimated for winter months (November–March) did not exceed 10–15% of the annual load. The estimated loads are sums of loading from river inflow, that is, from the Jorka river (and from larger streams such as Baranowska stream flowing to Lake Jorzec; see Fig. 1 and Hillbricht-Ilkowska 2002a), surface runoff to the lake from the direct active watershed, and atmospheric input directly on the lake surface.

Inflow with river waters (that is, with the Jorka river and the stream Baranowska) (Fig. 1) was estimated as a product of the discharge and concentration of nutrients, measured at monthly intervals at the outlets of the river to successive lakes. Surface runoff from the direct basin of the lake (with exclusion of the land depressions that do not contribute to surface runoff) (Table 1) was estimated as a sum of loads carried every month by small streams monitored and described by Rybak (2002 b) (Fig. 1). For the parts of the direct lake basin that were not monitored (that is, after subtraction of the monitored streams), the same values of the unit surface runoff (in kg ha^{-1} $month^{-1}$) were assumed as those obtained for the monitored streams with a similar cover and use. These parts of lake basins (that is, parts that were not drained by streams) contributed from 12% (Lake Inulec) to 60% (Lake Jorzec) of the lake basins. For the smallest, throughflow Lake Zełwążek, the whole direct basin was not monitored be-

Table 1. The areas included into the calculation of surface runoff to lakes of the Jorka river system: total lake catchment including river inflow (km^2), percentage of the areas without surface outflow, the direct and active catchment (without the river catchment and the area not active in surface runoff), the part of lake catchment drained by the monitored streams and the part of lake catchment not monitored, in km^2. Data for successive lakes acc. to Bajkiewicz-Grabowska (1985) with later corrections and acc. to Rybak (2002b).

Lake	Total catchment (km^2)	% of area without surface runoff	Direct active catchment (km^2)	Catchment of monitored streams (km^2)	Not monitored part of catchments (km^2)
Majcz	18.90	70	5.87	3.67	2.20
Inulec	8.69	0	8.69	7.75	0.94
Głębokie	2.24	0	2.24	1.36	0.88
Zelważek	0.76	12	0.54	–	0.54
Jorzec	2.05	3	1.98	0.63	1.35

cause of absence of streams flowing into this lake (except for the Jorka river) (Table 1).

Previous studies of the Jorka river basin conducted in 1978–1979, did not show a significant contribution of ground waters, that is, from the water-bearing horizon below the depth of drainage by surface water, as it did not exceed 15% and typically was a few percent of the inflow and outflow (Bajkiewicz-Grabowska 1985).

Atmospheric input of TP, $N\text{-}NO_3$, and $N\text{-}NH_4$ in dry fall and with rainwater was estimated based on the data provided by the Station of the Background Monitoring "Puszcza Borecka", located about 50 km east of the Jorka river basin, that were published by the Institute of Environmental Protection (Degórska 1997, 1998, 1999, Śnieżek 1997) (Table 2). It should be noted that TP loads with rainfall were lower in 1996 than in 1997 and 1998, whereas the loads of nitrogen were more or less similar over the three study years, or slightly higher, as in the case of $N\text{-}NO_3$ in 1997–1998 compared to 1996. No soluble organic forms of nitrogen were analysed in atmospheric precipitation, which is likely to reduce the estimated total nitrogen input by an unknown quantity, though it does not seem to exceed 30% of the total nitrogen input, as implied by the results of Kufel (1996), who analysed concentrations of Kjeldahl nitrogen and nitrate nitrogen in precipitation in 1986–1988.

Table 2. Nutrient input to lakes of the Jorka river system (in mg m^{-2}) with precipitation for the periods April–October of different years. Data acc. to Degórska (1997, 1998, 1999) and Śnieżek (1997)

Nutrient	1996	1997	1998
TP	43.0	18.6	26.7
$N\text{-}NO^3$	168.0	192.4	19.2
$N\text{-}NH^4$	297.0	228.0	311.0

In addition to the total load from the three sources combined, also the contribution of each of these sources to the total load was estimated for each lake. These estimates should be considered fairly reliable and real, as they are based on measurements *in situ*.

The above estimates of the annual loading (in fact, for a period of April–October) for 1996–1998 were compared to those for 1978 published in Hillbricht-Ilkowska and Ławacz (1983) and also based on measurements *in situ* of the river inflows to and outflows, from the same small streams draining the direct lake basins, as well as on measurements of N and P concentrations in precipitation (Goszczyńska 1983, 1985). In both these periods, the results concern the growing season, that is, they cover the period of spring flood and summer-autumn maxima of precipitation. In 1978, no $N\text{-}NO_3$ concentration was measured in the atmospheric precipitation and in streams or the river, so the respective values of TN were based on the proportion of this nitrogen form in total nitrogen (TN) found in similar studies conducted in this region (details in Hillbricht-Ilkowska and Ławacz 1983).

Comparing the total loading of successive lakes from all the three sources with the loading in the outflow from these lakes, retention (R) of particular compounds in lakes was calculated as a ratio of the difference between the input (*I*) and the output (*O*) to the input, in percentage:

$$R\ (\%) = (I - O) : O \quad (1)$$

This is a measure of so-called external budget. A positive value of retention indicates net accumulation of a compound in a lake in particular periods, and a negative value indicates net export, which means that in a given period more nutrients leave a lake than flow into the lake from all the sources jointly. Retention calculated in this way is commonly used for estimating the role of different ecosystems in biogeochemical processes occurring in the landscape, for example, in wetlands (Kruk 2000) or lakes (Hillbricht-Ilkowska 1993, 1999a, b), and is an objective measure of this role.

4. RESULTS

4.1. LOADS: ANNUAL ESTIMATES, LONG-TERM AND SEASONAL CHANGES, CONTRIBUTION OF DIFFERENT SOURCES, COMPARISON WITH OTHER LAKES

When comparing data from 1978 and 1996–1998, and among successive years of 1996–1998 (Table 3), the following major tendencies can be identified in long-term variation. In most cases, TP and TN loads in 1997–1998 were lower than in 1978. In a few cases, all the data from 1996–1998 were lower than in 1978. This tendency was especially noticeable for TN loads in all successive lakes of the system, whereas less clear for TP loads in that typically the values for 1996 were the highest or equalled that from 1978. Moreover, differences between years were more clear for higher situated lakes (Majcz, Inulec, Głębokie) (Table 3). It should be emphasized that occasionally loads differed by one to two orders of magnitude in different years. This was especially the case of nitrogen loads that decreased from 51.8–2.47 in 1978 to 14.0–0.5 g m^{-2} of lake surface per year in 1998. Analogical variation in TP loads ranged from 1.1–0.07g m^{-2} year^{-1} in 1978 to 1.45–0.021 g m^{-2} year^{-1} in 1997–1998, but with a tendency to generally lowest values in 1997 (Table 3). In each study year, a clear spatial variation was observed, related with the location of a lake in the system. For example, the lower the lake, the greater the load per surface unit. This is consistent with the spatial differentiation of the human impact in the catchment and changes in unit export rates described by Rybak (2000, 2002b).

The high TP and TN loads in 1978 in Lake Głębokie were primarily an effect of a trout aquaculture. The inputs of TP and TN from this point source were calculated by Penczak *et al.* (1985), and amounted to 77% and 56% of annual values, respectively (Table 3). This aquaculture was stopped in 1994, so the decline in loads to this lake in 1996–1998 seems to be a result of the removal of this source of pollution. This does not explain, however, changes observed in 1996–1998.

As a result of a clearly higher decline in annual TN loading as compared to TP loading, the ratio of these two eutrophicating nutrients decreased in the sources of the

Table 3. Loads of TP and TN in g m^{-2} of lake area, for period April–October (taken as close to the annual value, see text) for successive lakes of the Jorka river system. Data for 1978 acc. to Hillbricht-Ilkowska and Ławacz (1983)

Lake	TP				TN			
	1978	1996	1997	1998	1978	1996	1997	1998
Majcz	0.077	0.168	0.021	0.031	2.47	2.07	0.55	0.64
Inulec	0.089	0.289	0.023	0.036	4.23	2.37	0.50	0.65
Głębokie	1.095[1)]	0.317	0.052	0.154	31.2[1)]	4.0	1.37	2.7
Zełwążek	0.796	0.967	0.431	1.454	51.8	9.0	6.0	14.0
Jorzec	1.032	2.043	0.472	0.762	27.8	17.9	5.5	7.6

[1)]In this year, the input from trout aquaculture was close to 0.84 TP and 17.4 TN g m^{-2} of lake area. It was about half of the total annual load to this lake.

external loading of particular lakes, and it was clearly lower in 1996–1998 compared to 1978. In 1978, it ranged between 65–27, depending on the lake, whereas in 1996, 1997, and 1998 the respective figures were 13–8, 26–12, and 21–10. In this three-year study period, the values for lower lakes (eutrophic and polluted) did not exceed 15, whereas for higher lakes (mesotrophic or moderately eutrophic) they were up to 26. This seems to provide evidence for an important change. Although absolute values of annual loads declined, the TN:TP ratio was close to the value that might indicate that phosphorus was no more the factor limiting for primary production of the phytoplankton.The value below 20:1, close to Redfield ratio, means that these nutrients are supplied in proportions corresponding to those in plankton biomass.

Phosphorus and nitrogen loading to lakes showed a clear seasonal variation. In each study year, at least 50%, and sometimes up to 95% (in 1996), of the annual load of all the three compounds took place in April–June (and in most cases, only in April and May) (Table 4). In 1996, the mean load of TN and TP in April was as high as 86% of annual value. This was an effect of a violent increase in river discharge and surface runoff due to a sudden rise in temperature (mean April temperature was +6.5°C) following the period of temperatures below freezing over January–March (from –2.6 to –7.1°C); the situation not noted in other years (Degórska 1995). Similar seasonal changes in loads were noted in the "wet" year of 1978 (Hillbricht-Ilkowska and Ławacz 1983).

These results imply that annual TP and TN loads were dependent on seasonal dynamics of the discharge, in the sense, that discharge during spring flood is of crucial importance.

Table 4. The percentage contribution of nutrient load in April, May and June to the total annual load for successive lakes of the Jorka river system. Range of values for 1996–1998. The highest value were recorded for 1996

Lake	TP	$N\text{-}NO^3$	TKN
Majcz	54–86	62–80	66–88
Inulec	50–92	54–86	56–89
Głębokie	73–86	61–66	66–90
Zelważek	84–95	62–79	74–95
Jorzec	60–94	67–93	58–88

The contribution of three principal sources of loads: river imput, surface runoff, and atmospheric input to the annual load of TP and TN was compared for different study years (Fig. 2). Depending on their location, some lakes were primarily loaded from the atmosphere, for example, Lakes Majcz and Inulec because of their size and location in the upper part of the basin, and some others were loaded mostly by the river, for example, Lake Głębokie located in the middle part of the basin, or almost exclusively by the river like, for example, Lakes Zełwążek and Jorzec, located in the final section of the Jorka river. According to Kratz *et al.* (1997), this sequence of load sources is typical of lake chains. Only in1996 this pattern was not followed, as loading from the surrounding land (for reasons described above) either with surface runoff (Lake Majcz) or with river input (the other lakes) predominated the annual TP and TN loads (Fig. 2). However, large differences existed in the contribution from different sources, land *versus* atmospheric, for $N\text{-}NO_3$ and TKN (sum of ammonium and organic nitrogen) loads considered separately (Table 5). Annual $N\text{-}NO_3$ load in 1996–1998 was more often dominated by atmospheric loading. Exception was the situation in 1996, when the input from the land runoff dominated even in the upper lakes of the system.

Annual TP loading values to the lakes of the Jorka river system were within the range of rather low values compared with other lake systems of the Masurian Lakeland (Table 6). No values higher than 2.0 g m^{-2} of lake sur-

Table 5. The percentage contribution of the nitrogen load from the catchment (river inflow and surface runoff) and from precipitation to the annual load of this element for successive lakes of the Jorka river system. Range of values for 1996–1998

Lake	source of input	Nitrate nitrogen	Organic and ammonium nitrogen
Majcz	catchment	3–63	28–82
	precipitation	37–97	18–72
Inulec	catchment	5–75	15–87
	precipitation	25–95	17–85
Głębokie	catchment	18–58	80–92
	precipitation	42–82	8–20
Zełwążek	catchment	62–72	96–98
	precipitation	28–38	2–4
Jorzec	catchment	18–58	80–92
	precipitation	42–82	8–20

Table 6. Comparison of the range of values of annual TP load expressed in g m^{-2} of lake area for three different groups of Masurian lakes according to different sources

Groups of lakes	Range of values	Dominates in annual load:
17 lakes of river Krutynia system[1]	1.8–25.1	River input
20 lakes of Suwalski Landscape Park[2]	0.054–9.45	River input and surface runoff
8 shallow and eutrophic lakes in Suwalski Landscape Park	0.55–5.05	River input and precipitation
5 lakes of the Jorka system		
1978[3]	0.077–1.1	River input and precipitation
1996	0.168–2.04	
1997	0.021–0.47	
1998	0.031–1.45	

[1]acc. Hillbricht-Ilkowska, Kostrzewska-Szlakowska (1996);
[2]acc. Hillbricht-Ilkowska (1994)
[3]acc. Hillbricht-Ilkowska, Ławacz (1983).

face $year^{-1}$ were recorded in 1978 or 1996–1998, and values between 0.01 and 0.1 g m^{-2} $year^{-1}$ were frequent. Such low values were rare in Suwalskie lakes (mentioned above) and absent from the throughflow lakes on the Krutynia river system (Table 6). Relatively low loadings to the Jorka river-lake system was determined by the fact that the contribution of atmospheric loading, that carries relatively lower loads than the surrounding land, was high in the largest and higher situated lakes of the Jorka river system. Moreover, the river system of the Jorka was little developed as compared, for example, with that of the Krutynia river, and water discharge was relatively small (below 1.5 m^3s^{-1}, Hillbricht-Ilkowska 1998) at the places of discharge to lakes. Also the proportion of pollution and touristic use in the load to Krutyńskie lakes was higher (Hillbricht-Ilkowska and Kostrzewska-Szlakowska 1996).

4.2. LOADING AND SEASONAL VARIATION OF DISCHARGE IN THE RIVER NETWORK; ANNUAL RATE OF WATER EXCHANGE

No linear relationship was found between annual precipitation and TP or TN loading. The evidence was provided by an unusual situation in 1996, when annual precipitation was low (below 500 mm) but TP and TN loads were very high due to the high discharge during a short period of the spring flood. Similarly, no linear relationship existed between precipitation and discharge and loads from small streams flowing into lakes (Hillbricht-Ilkowska 2002a, Rybak 2002b). Thus, the annual loading of these nutrients was determined mainly in the short spring period, that differed depending on the year. Loading in the remaining seasons did not contribute significatly the annual loading, although precipitation might be high. This implies that seasonal and annual variation in nutrient loading was directly determined by seasonal variation in discharge within the river network, both permanent waters such as the Jorka river or the stream Baranowska (Fig. 1) and smaller, intermittent streams that determined non-point runoff from the land (see Rybak 2002b). Consequently, the annual outflow (Q) from successive lakes of the Jorka river system and the rate of water exchange (as a ratio of outflow to lake volume) were compared in different years (Table 7). The outflows from all the lakes were much lower in 1996–1998 compared with 1978–1979; they were reduced at least by half or to one-third, and occasionally to one-tenth (e.g. Lake Inulec) (Table 7). This difference does not seem to depend on the fact that the value of Q for the 1970s also includes the winter period (Bajkiewicz-Grabowska 1985), as those data had no significant influence on annual estimates. As a result, the annual rate of water exchange in lakes markedly declined, especially in the largest lakes in the upper river section (Lakes Majcz, Inulec); (Table 7). Annual water exchange in lakes occurred mainly in the period April–June (Table 8). In the 1990s, thus, water resources of the Jorka river and its discharges were considerably lower, and the lakes became more

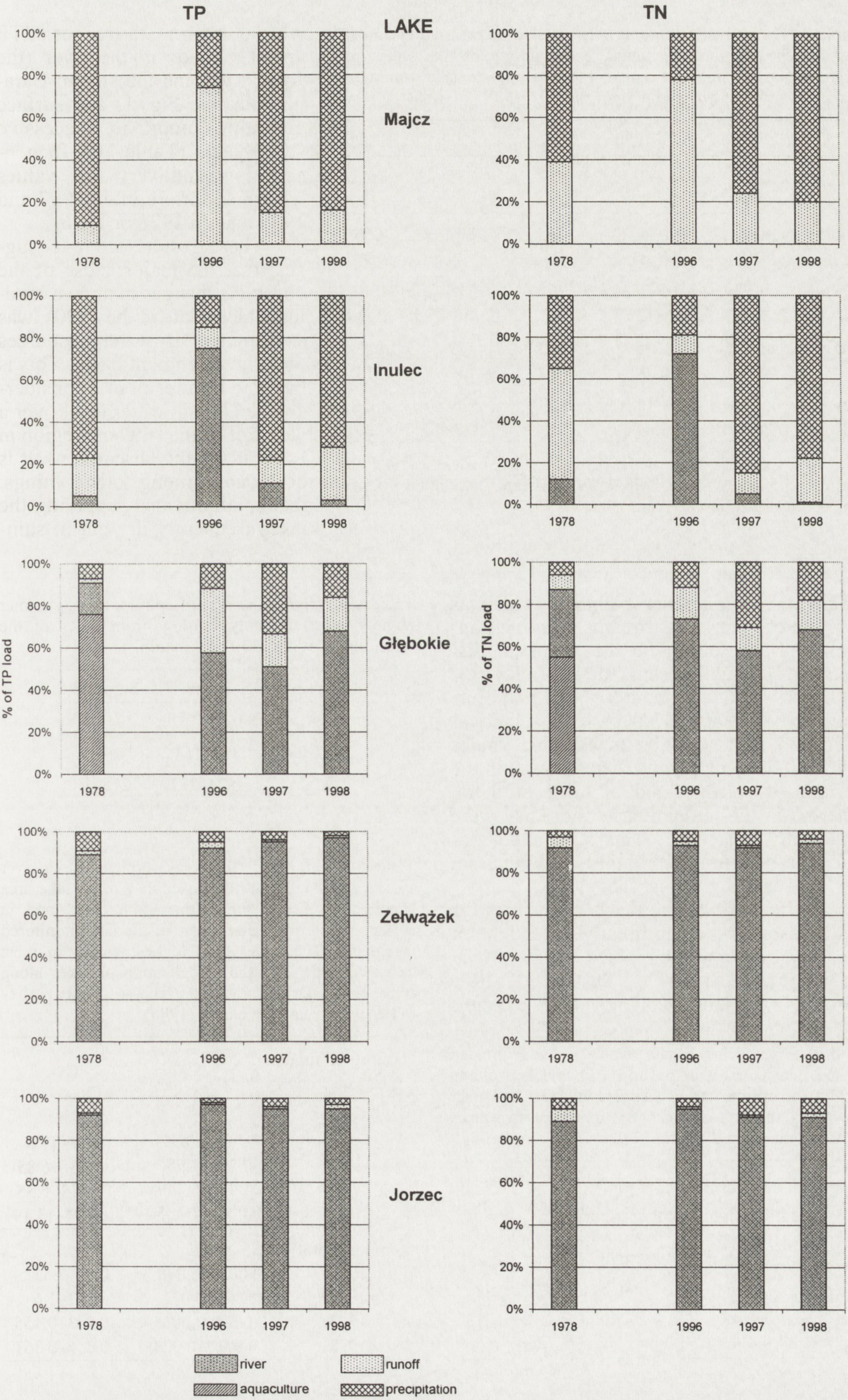

Fig. 2. Percentage contribution of different sources in the annual load of TP and TN for successive lakes of the Jorka river system in different years. Data for 1978 – according to Hillbricht-Ilkowska and Ławacz, 1985.

Table 7. The annual outflow (Q, 10^3 m^3) for successive lakes of the Jorka river system and the annual exchange rate of lake water (in %) expressed as the ratio of annual outflow (Q) to lake volume (V). Data for different years and sources.

Lake		1978–1979[1]	1996	1997	1998
Majcz	outflow	2263–3143	562	735	1172
	Q/V	23–32	6	7	12
Inulec	outflow	1920–4724	865	307	656
	Q/V	26–63	12	4	9
Głębokie	outflow	2560–7036	670	718	1251
	Q/V	46–126	12	13	22
Zelwążek	outflow	2595	683	577	923
	Q/V	610	162	137	218
Jorzec	outflow	4629–10814	1769	909	4338
	Q/V	222–468	77	39	180

[1]acc. to Ławacz (1985) and Bajkiewicz-Grabowska (1985). The range of values for 1978–1979 indicates variation between hydrologically different years.

when comparing the ranges of TP and TN loads in the river (the Jorka river and the stream Baranowska, see Fig. 1) and surface non-point runoff in successive study years (Table 10). In general, low and very low values were noted more often 1997 and 1998 than in 1978 or 1996.

These results seem to suggest that the major cause of the observed changes in annual loading, at least late in the 1990s, was a decrease in water resources over the catchment basin. This is likely to be a result of a considerable decline in water level over a vast area of the lakeland region in Poland (see the Discussion). It is observed, among other things, that small streams supplying the lakes frequently dry out in sum-

stagnant with a smaller exchange. This was also the case of small streams carrying non-point surface load. The mean annual discharge of 10 small streams (details in Rybak 2002b) in 1996 was about 67 (±40.7%) of its value in 1978, 20 (±13.0%) in 1997, and 43 (±16.3%) in 1998. The measurable values (above 0.0003 m^3 s^{-1}) were noted only in the periods of spring flood in most of them, whereas in the remaining periods they were practically "inactive". This seasonal variation also determined monthly outflows from the lakes as it is given in Table 9.

In 1996–1998, the discharge values for both seasons were not directly dependent on monthly precipitation (see Fig. 3 in Hillbricht-Ilkowska 2002a, Rybak 2002b). The same tendency also emerges

Table 8. The exchange rate of lake water expressed as the percent ratio of outflow (Q) to lake volume (V) in the spring period (April–June) (A) and over the year (April–November) (B) for successive lakes of the Jorka river system

Lake	1996 A	1996 B	1997 A	1997 B	1998 A	1998 B
Majcz	3	6	4	7	7	12
Inulec	11	12	3	4	8	9
Głębokie	10	12	10	13	21	22
Zełwążek	148	162	98	137	210	218
Jorzec	70	77	16	39	147	180

Table 9. Spring (April, May) and summer (June–August) monthly outflow from lakes of the River Jorka system (10^3 m^3 $month^{-1}$)

Year	Spring	Summer
1996	1003–151	94–1
1997	392–154	105–10
1998	1874–227	215–1

Table 10. The range (for 5 lakes of the Jorka river system) of annual nutrient loads in g m^2 of lake area supplied by river input (the Jorka river) and in surface runoff from direct part of the lake monitored catchment. The lowest and highest values in most cases coincide with the localization of lakes along river flow. Data for 1978 acc. to Hillbricht-Ilkowska and Ławacz (1985)

Source of input / Year of study	TP	TN
River input		
1978	0.0035–0.96	0.27–47.8
1996	0.202–1.98	1.68–16.85
1997	0.0003–0.449	0.013–5.55
1998	0.0003–1.425	0.004–13.19
Surface runoff		
1978	0.0035–0.018	0.97–2.53
1996	0.020–0.072	0.171–1.6
1997	0.0025–0.0065	0.043–0.155
1998	0.0028–0.024	0.206–0.361

mer, connections between lakes are temporarily interrupted, the system becomes hydrologically discontinuous, and lakes are often isolated. Thus, the basic reason for annual variation in loading would be changes in water discharge, rather than changes in concentration of nutrients.

A consequence of a small mobility of river and lake waters is their small hydraulic loading (calculated as a ratio of annual outflow to the lake surface area) – a parameter which is a component of the so-called permissible loading and its value twice as high i.e. dangerous loading. According to Vollenweider (1976), this is a phosphorus load at which TP concentration during the period of spring turnover can be maintained at a level not higher than 20 mg m^{-3}, that is, at the level that does not trigger algal blooms. The values of the permissible load for Lakes Majcz, Inulec, and Głębokie in 1978 and 1996 were higher than or equal to the estimated annual load or even higher than the dangerous value. They indicate the category II or III according to the classification proposed by Hillbricht-Ilkowska (1994) (also in Hillbricht-Ilkowska and Kostrzewska- Szlakowska 1996). In 1997–1998, however, they indicated threat category I or II that is, the estimated load was lower than or equal to the permissible load because of reduced loading and lower water mobility. In the lowest lakes, Zełwążek and Jorzec, the estimated load was greater than dangerous value, that is, these lakes showed category III of threat with further eutrophication. It can be stated that although the general direction of changes was positive, especially in 1997–1998, the lakes situated in the lower Jorka river are permanently vulnerable to eutrophication.

Table 11. The percentage values of annual TP retention (the difference between the load in input and outflow, expressed as % of input) for successive lakes and years of the study. Note the negative values!

Lake	1978[1]	1996	1997	1998
Majcz	–	83	48	15
Inulec	59	80	86	20
Głębokie	82	25	–92	–46
Zełwążek	–	3	34	44
Jorzec	46	60	73	–36

[1]after Ławacz (1985).

4.3. RETENTION OF PHOSPHORUS AND NITROGEN IN LAKES; LONG-TERM CHANGES

The difference between the cumulated loading from all the sources and the cumulated outflow with the river over the period April–October gives an estimate of nutrient net retention in the lake, expressed in percent of the loading (see the Methods). A positive retention provides information about the scale of the cumulation of external load in the lake, while negative retention informs about the scale of net export from the lake. In the case of export, we have to do with "production" of a nutrient in the lake ecosystem outweighing its input from the land and atmospheric surroundings. This situation is typical of TP retention in lakes in summer when it is released from sediments under conditions of the summer oxygen deficit. As a result, the internal load of this nutrient in the lake is higher than its external loading. In this situation, the calculated loading in the water outflow from the lake can seasonally, or even at the scale of a year exceed its input.

For three lakes of the Jorka river system, Ławacz (1985) compared in detail TP loading in successive months and changes in TP mass in the lake in the same periods. He concluded that the latter was temporarily determined by internal inflow, that is by release from bottom sediments. But the net result over the growing season (Table 11) showed a positive retention in all lakes; it was highly positive for Lake Głębokie (about 80% of TP loading was retained in the lake, mostly in available form derived from cage culture of the trout), a little lower (about 60%) for eutrophic, shallow Lake Inulec, and the lowest (about 40–50%) for heavily eutrophicated, polluted Lake Jorzec carrying waters from the whole Jorka river-lake system (Table 11). The values of TP retention calculated for successive years of 1996–1998, that is, when the loading of this nutrient and discharge from successive lakes were lower than in 1978, show specific changes. The annual net TP retention in lakes tended to decrease, and even its net export from the lakes became frequent (Table 11). This was the case of 4 out of 5 lakes, and can be seen when the results from 1998 or 1997–1998 are compared with those from 1996 and 1978 (Table 11). The TP retention in higher situated lakes (Majcz, Inulec) was reduced to 1/2–1/4, and the lower lakes (Głębokie and Jorzec) shifted to the systems "exporting" this nutrient at the annual scale (negative retention values Table 11). The only exception was the small, throughflow Lake Zełwążek, where retention was positive all the time (Table 11). These long-term tendencies in the functioning of lakes with respect to TP transport can also be illustrated by a marked increase in the number of cases of negative retention values for monthly periods in 1998 compared with 1997 and 1996 (Table 14).

The same tendency was observed for the retention values of TKN, that is, organic and ammonium nitrogen combined (Tables 12 and 14). It was lower in 4 lakes in 1997 and 1998 compared with 1996, and negative values were more frequent (Table 14). In Lake Jorzec, that closes the Jorka river-lake system, the loading in outflowing water in 1998 was higher than the input (retention = 147% of the input). In the whole lake system, also an increase was noted in the frequency of negative monthly retention of TKN (Table 14).

The pattern of changes in N-NO_3 retention in the three-year period of 1996–1998 differed from that of TP and TKN (Tables 12 and 13). Its retention was high, higher for Lakes Majcz and Inulec, a little lower for lower lakes. Only in lake Jorzec in 1998 retention of this compound was negative – the lake "exported" it, like TP and TKN in that year. The number of cases with negative monthly retention of N-NO_3 was low and it did not vary in 1996–1998 (Table 14).

This analysis of the pattern of changes in nutrient retention in 1978 and the three-year period of 1996–1998 yields the following conclusions. Loading of TP and TKN (mainly from the land in the river inflow and surface runoff, occasionally atmospheric input) is cumulated in lakes of the Jorka river-lake system in progressively lower quantities, so that even internal sources of these nutrients (release from sediments, decomposition processes, biological nitrogen fixation) can be more important than external sources, giving rise to the exportation of these nutrients to lower fragments of the system (that is, retention is negative). These changes are accompanied by declining annual loading and declining discharges in the entire system, as noted in the 1990s compared with the 1970s. In contrast, the loading of nitrate nitrogen, derived from both the atmosphere and the land, was permanently high and it did not vary in 1996–1998. It seems that denitrification processes in different lake habitats, especially in sediments rich in organic matter and without oxygen, are responsible for the "loss" of nitrogen from this compound. This is a very efficient process, particularly in eutrophic lakes, shallow and with organic sediments, rich littoral and macrophytes, as found, for example by Ahlgren *et al.* (1994).

Table 12. The percentage values of annual TKN (organic + ammonium nitrogen) retention for successive lakes of the Jorka river system and years of the study. Note the negative values!

Lake	1996	1997	1998
Majcz	99	10	–2
Inulec	65	15	–18
Głębokie	40	1	5
Zełwążek	–19	22	34
Jorzec	35	35	–147

Table 13. The percentage values of annual N-NO_3 retention for successive lakes of the Jorka system and years of the study. Note the negative values!

Lake	1996	1997	1998
Majcz	90	97	95
Inulec	93	99	95
Głębokie	73	88	79
Zełwążek	–	87	73
Jorzec	73	96	–31

Table 14. The number of cases of positive values (+) (i.e. when a part of the input is accumulated in the lake) and negative values (–) (i.e.when the load in outflow is greater than in input) of monthly nutrient retention. Data for whole group of five lakes of the Jorka river system and for successive study years

Nutrient	1996		1997		1998	
	+	–	+	–	+	–
TP	29	6	25	8	20	15
TKN	25	10	24	11	20	15
N-NO[3]	26	5	33	0	30	3

5. CONCLUSIONS AND DISCUSSION

A declining tendency was observed in phosphorus and nitrogen loading to lakes from external sources (river inflow, surface runoff, atmospheric input) in the 1990s, especially in 1997 and 1998, compared with the 1970s and/or 1996. The reduction of loading is mainly a result of lower discharge and volume of water in the system in periods beyond the spring period. The two study periods differed in weather conditions. A little lower precipitation and higher temperatures were noted in 1996–1998 than in 1977–1979, the latter being wetter and cooler. The nitrogen loading was more reduced than phosphorus loading, thus N:P ratio in sources of loading declined, approaching the value close to that in algae (below 20:1).

The annual loading is determined during the short period of spring flood (melting of ice and snow cover, thawing of the soil). It may be said that lakes are becoming similar to so-called "pulsed systems", this term being introduced by Junk (1997) for seasonally regenerated riparian habitats. For shallow lakes of the temperate zone that are subject, as it seems, to global warming and changes in land use, pulsed regeneration would concern nutrient and matter supply in lakes. In the period beyond the spring flood, the river system and surface runoff become discontinuous, the loading is small, and lakes become frequently isolated, with a low water exchange rate. Inflow to and outflow from successive lakes become irregular and asynchronous, and nutrient loading variable and unpredictable. There is no direct relationship with seasonal dynamics of precipitation. This situation seems to be a consequence of a substantial decrease in the ground water level observed over vast areas of the lowland (Kleczkowski 1994, Hillbricht-Ilkowska 1997) combined with the changes in regional climate (increase of air temperature, variable precipitation, frequent drought). Similar results are reported by Mander *et al.* (1998), who found that a decrease in nitrogen and phosphorus export from agricultural basins to Estonian lakes was, among other things, a result of reduced discharge in summer periods, and correlated with frequent droughts and general climatic changes.

Atmospheric input and surface runoff were the major sources of the annual TP and TN loading to large lakes in the upper part of the basin (Lakes Majcz and Inulec), whereas nitrate nitrogen loading originated from these two sources in all the lakes. Phosphorus and organic plus ammonium nitrogen loading to the lakes in the middle and lower parts of the basin originated mainly from the river inflow and land surroundings of the lakes. In each study year, directional changes in loading were observed, as loading was lower in upper lakes and higher in lower lakes. Similar results were obtained by Soranno *et al.* (1999) for lake chains in North America.

With declining nutrient loading and water mobility in the Jorka river-lake system, a tendency was observed to reduced retention of phosphorus and organic + ammonium nitrogen in successive lakes and study years, and even to a temporal export of these nutrients with water outflow from the lake as compared with their inflow loading. Thus, internal sources of these nutrients, such as release from sediments and biological nitrogen fixation, become more important than external sources. Irregular outflows from lakes can carry loads equal to or even higher than the inflow loading to the lakes. Typically, the retention of nitrate nitrogen is high and positive, implying that nitrogen loss as an effect of denitrification in lakes may be efficient.

The decline in TP and TN retention (and sometimes negative retention at the annual scale) when water retention in lakes increased in 1996–1998, requires a more detailed explanation as it seemingly contradicts the assumption of the models of OECD (Vollenweider 1976; Smith 1993) that phosphorus retention increases with water retention. It should be remembered, however, that this model does not concern situations when phosphorus load in the outflow is temporarily higher than in the inflow. Schindler (1997) clearly shows that increased water retention in lakes (as a result of reduced surface water resources, drought and absence of precipitation, that is, climatic changes) do not have to be accompanied by increased nutrient retention, that the response of each lake to these factors is complex and difficult to predict at the short-term and long-term scales. This author describes a system with a high but short-lasting inflow to a lake in spring as a result of climatic changes and low but prolonged outflow. Then the ratio of inflow to outflow loading may vary even in favour of the latter. This is especially the case of nutrient loading to and from successive lakes of a river-lake system. Such lakes can function as a "sink" or as a "source" of nitrogen and phosphorus compounds, periodically or over the year (Soranno *et al.* 1999, Hillbricht-Ilkowska 1993, 1999a). Tendencies to export (i.e "source" type of the system functioning) occur in lower situated lakes, for which the river is the main source of loading, as it can be seen in the Jorka river-lake system.

As a result of reduced TP and TN loadings and tendency towards their reduced retention in lakes, the trophic conditions and productivity of the lakes of the Jorka river did not exhibit coherent directional changes towards advancing eutrophication in corresponding periods of the 1970s and the1990s (Hillbricht-Ilkowska 1998, 2002b).

In lakes situated in the lower parts of the basin, that were the most polluted and affected by agriculture, estimated loadings permanently exceeded the calculated dangerous loads (threat category III) in both the 1970s and the 1990s. The situation in Lake Głębokie was improved in 1997–1998, among other things because of stopping the trout aquaculture but the lakes in the upper part of the system showed signs of a moderate increase in eutrophication rate, as the estimated loads were equal to or higher than the permissible loads but not higher than dangerous ones. The trophic state of the study lakes seems to be relatively stable, as no directional changes were observed in such indices as water transparency (Secchi Disc readings), chlorophyll concentration, phosphorus concentration, or algal biomass. Although these indices of trophic conditions largely vary, no trends are observed (Hillbricht-Ilkowska 1998).

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6. SUMMARY

External nutrient loading was assessed over several years for five lakes (mostly shallow and eutrophic) located in the catchment basin (area 65 km^2) of the river-lake system typical of a lakeland region (the Jorka river system, Masurian Lakeland, Poland) (Fig. 1).The discharge and concentration of TP, TKN (organic and ammonium nitrogen) and N-NO_3 were measured monthly in the river input to and outflow from successive lakes (Fig. 1), in surface runoff (monitored streams, Fig. 1) from direct, active lake subcatchments (Table 1), and in precipitation (Table 2), for the periods April–October of 1978 (adopted from Hillbricht-Ilkowska and Ławacz, 1985) and 1996–1998.

A general tendency to decrease in nutrient loading (g m^{-2} lake area) to lakes was observed when comparing 1997–1998 with 1978 and/or 1996 (Table 3). The decrease was stronger for TN than TP. At least 50% of the annual loading took place during spring freshet (Table 4). River input and/or precipitation dominated in the annual loading of TP and TN (Fig. 2), however the exact values are dependent on the location of lake in the system (Fig. 2). Precipitation tended to dominate in the load of nitrate-nitrogen, whereas input from the catchment – in the load of other forms of nitrogen (Table 5). Generally, nutrient loading to the lakes of the river Jorka was found to be lower than to lakes of other river systems in Masurian Lakeland (Table 6).

Due to the decrease in the river outflow from successive lakes in the years 1996–1997 *versus* 1978–1979, the annual exchange rates of lake water decreased (Table 7), being the highest in the spring period (Tables 8 and 9). As a result of lower discharge in the whole system, the nutrient loading with the river and surface runoff also tended to decrease (Table 10).

The monthly and annual retention of nutrients was calculated for successive lakes and years of the study. Retention was expresed as the percentage difference between input and outflow loads. A general decrease in retention values was found for TP and TKN in all lakes, including the negative values for the years 1997–1998 (Tables 11, 12, 14). The retention of N-NO_3 remained highly positive almost in all cases (Table 13) which indicates an effective in-lake denitrification.

It seems that irrespective of the lower values of loading to lakes, a smaller part of it was retained in the lake systems; lakes became the source of nutrients for the downstream fragments of the river system.

It is suggested that under dry and warm weather conditions (like in 1997–1998), nutrient and hydraulic loads to lakes decrease considerably, the relations between inflow and outflow become disturbed, and the shallow, eutrophic lakes begin to export nutrients; the internal loading seems to be more intensive that the external loading under these conditions. The importance of this situation to the prediction of the effects of global warming in small catchments is pointed up.

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