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EUTROPHICATION RATE OF LAKES IN THE JORKA RIVER SYSTEM (MASURIAN LAKELAND, POLAND): LONG-TERM CHANGES AND TROPHIC CORRELATIONS

ABSTRACT: No trends were found in long-term variation (between the1970s and the1990s) of basic trophic parametres (TP,TN, chlorophyll concentration, algal biomass, and water transparency) in five lakes of the river-lake system typical of a lakeland, hilly area (the Jorka river system, Masurian Lakeland). Recently, this lake chain maintains the historically developed trophic differentiation between deep, mesotrophic lake close to headwaters and shallow, eutrophic lake close to the outlet of the river. The only change found is the replacenemt of cyanobacteria dominating in the 1970s by dinoflagellates dominating in the 1990s. A strong correlation was found between TP loading to lakes and in-lake TP concentration in spring periods, however no correlation existed between TP and other trophic indices. On the other hand, the interrelations between SD, chlorophyll, and algal biomass were highly significant in summer periods and marginally significant in spring periods. This pattern was also found in other groups of lakes in the region. It is concluded that in hilly lakeland region, the river-lake systems draining small mosaic catchments are resistant to the further eutrophication (low nutrient loading, no point sources) and for this reason they tend to maintain the trophic conditions developed in the remote past.

KEY WORDS: long-term studies of eutrophication, trophic correlations, river-lake system

1. INTRODUCTION

Lake eutrophication, whose symptoms include an increase in fertility, algal blooms, overgrowing of shallow parts, and oxygen depletion in water and sediments, is a global process, although dependent on local conditions that determine its rate.

The degree of lake eutrophication is typically characterized in terms of nutrient concentration, that is, phosphorus (TP) and nitrogen (TN) concentrations, ratio of these nutrients in water (N:P ratio), water transparency measured with Secchi disc (SD), chlorophyll concentration, phytoplankton biomass, contribution of some groups of algae, especially of cyanobacteria, oxygen depletion in the hypolimnion, and others. These parameters are commonly used in trophic classification systems of lakes, such as used in OECD (Vollenweider 1989), also in Poland (Cydzik *et al.* 1995), as well as proposed by Kajak and Zdanowski (described in Hillbricht-Ilkowska *et al.* 1996). Most often, the estimates are based on measurements taken in the period of summer stratification, or calculated as mean values for the periods of summer stratification and spring mixing.

Searching for functional relationships and correlations between nutrients, especially P, and these measurable symptoms of eutrophication (chlorophyll, SD, algal biomass, and others) for various lake systems is permanently in focus of limnologists. For various groups of Polish (mainly Masurian) lakes, they were analysed by Zdanowski (1982), Uchmański and Szeligiewicz (1988) and Kufel (1999) and for the lakes of selected river catchment basins by Hillbricht-Ilkowska (1993) and Hillbricht-Ilkowska *et al.* (1996).

These relationships provide a basis for lake restoration to reduce TP input and to predict the effects of this treatment. Relationships between TP concentration and chlorophyll vary, depending on the absolute values of TP concentration and the values of the N:P weight ratio (a concise overview in Smith 1999 and Guilford and Hecky 2000). Typically, at low TP concentration in water (oligo-mesotrophic lakes) and N:P weight ratio not higher than 17–20, the relationship between TP and chlorophyll is, positive, linear or hyperbolic. At higher TP concentration, especially at low N:P ratio, the respective points diverge, and the relationship is not unambiguous (eutrophic and hypertrophic lakes). As a rule, when N:P ratio is low (below 10), nitrogen is a limiting factor, and the high phytoplankton biomass is dominated by cyanobacteria, including those nitrogen-fixing. Such systems typically develop as a result of cultural eutrophication, that is, a long-term phosphorus supply from point sources (sewage). The relationship between TP concentration and chlorophyll also depends on the dominant species of the phytoplankton (for example, on the dominance of cyanobacteria), on the presence of organic suspension (detritus with a different phosphorus content), mineral turbidity (suspension of inorganic particles), and on other factors (a review in Kufel 2000). For these reasons, differences in this relationship are observed between shallow polymictic lakes (frequent resuspension of sediment increasing turbidity) and deep stratified lakes (Kufel 1999). Also the intensity of filtering by the zooplankton, especially when in the zooplankton *Daphnia* species dominates, largely influences the TP-chlorophyll relationship (Andersen 1997).

As technical treatments can broadly eliminate phosphorus from point sources, like wastewaters, the rate of eutrophication will be dependent on nutrient loading from non-point sources such as river network, direct surface runoff from the catchment, and precipitation. It may be expected that the input from these sources will be lower than from point sources, thus, the rate of eutrophication will be reduced, but the evidence requires many years of observations.

The objectives of this paper are focused on the following questions:

- Do changes in the trophic status of a few lakes supplied mainly from non-point sources and connected in a river-lake system are detectable based on changes in the typical trophic indices measured in the 1970s and 1990s?
- Does a functional relationship exist between the trophic status of a lake and nutrient load, and do correlations exist among different and variable indices of the lake trophic state?
- Does the location of a lake in the river-lake system influence the actual trophic condition of this lake and the rate of further changes?
- What is the predicted rate of lake eutrophication under conditions of a mosaic postglacial landscape, moderate human impact, and possible climatic changes?

The present study is a part of a larger programme concerning the functioning of lakes in the Masurian Lakeland landscape, whose scope and main objectives are described in Hillbricht-Ilkowska (2002a).

2. STUDY AREA AND METHODS

The Jorka river (15 km in length) hydrographical system (Fig. 1) with its medium size catchment (about 65 km^2) is typical of the postglacial landscape of the Masurian Lakeland (north-eastern Poland). The river flows through five lakes which form a lake chain (Fig. 1). The large, deep, and mesotrophic Lake Majcz is located in the upper part of the system (recently, it has a bifurcated position in the system), whereas the small, shallow, and highly eutrophic Lake Jorzec is situated in the lowest part (Fig. 1). Besides the river, the lakes are supplied by many small streams (usually intermittent, active in spring freshet) but some of them are polluted with waste waters (Lakes Jorzec and

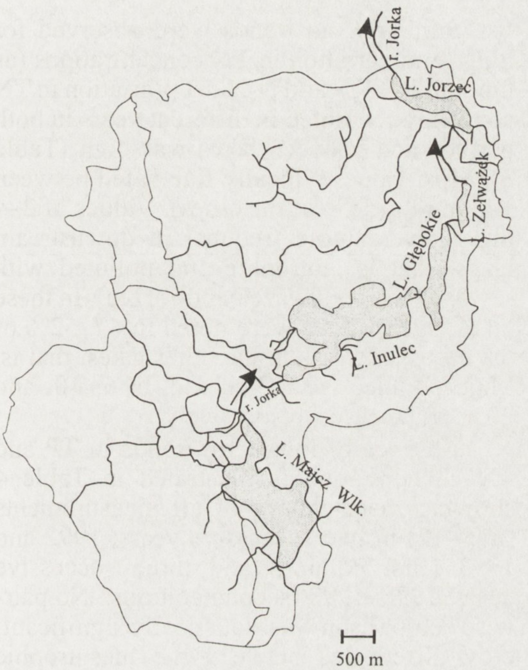

Fig. 1. The outline of the Jorka river system with location of successive lakes

Zełwążek). In L. Głębokie, an aquaculture of the rainbow trout was continued until 1994 and it was a dominant source of nutrients (Penczak *et al.* 1985). The basic morphometric characters of the lakes are set in Table 1. The flow of river between the lakes was usually not higher than 1.5 m^3 sec^{-1}, mostly between 0.1 and 0.01 m^3 sec^{-1}. The rate of water exchange in lakes was the longest (years) for the upper lake and the shortest (months) for downstream lakes. The river catchment was strongly differentiated along the river course: low human impact dominated in the upper part (forested area), and moderate to high human impact prevailed in the middle and lower parts of the catchment, respectively (arable land, pastures, cultivated meadows, forest islands, villages). The details of the catchment structure, land cover, agricultural impact, and pollution are given in Hillbricht-Ilkowska (2002a, b) and Rybak (2002a).

Concentration of TP, TKN (i.e. the sum of organic and ammonium nitrogen as the Kjeldahl nitrogen), N-NO_3 and chlorophyll in the study lakes of the Jorka river system were measured during springs (May) and summers (August) of 1992, 1993, 1996, 1997, and 1998 in surface layers to characterize the epilimnion, and over-bottom layer (about 1 m above the bottom) to characterize the hypolimnion. In the same periods, also thermal-oxygen stratification was analysed to estimate the depth of the layer with oxygen deficit, and water transparency was measured using a white disk. In 1996–1998, quantitative samples of the phytoplankton were taken also in the spring and summer periods. The biomass and contribution of the major phytoplankton groups were estimated (I. Jasser, unpublished). The values of these parameters for different years of the 1990s were compared with those for the 1970s published in Hillbricht-Ilkowska and Ławacz (1983), Planter *et al.* (1983), and Spodniewska (1983). Several-year study periods in the 1970s and the 1990s differed in terms of weather conditions as described by

Table 1. Morphometric data for lakes of the Jorka river system

Lake	Area (km^2)	Volume (10^3 m^3)	Depth (m) max.	Depth (m) mean	Shoreline (km)	Max. length (km)	Max. width (km)	% hypol.[2] in lake V (depth)
Majcz	1.74	9862.8	16.4	6.0	7.85	2.70	1.20	17.5 (<8 m)
Inulec	1.61	7500.01	10.1	4.6	10.6	2.40	0.90	22.0 (<5 m)
Głębokie	0.46	5601.0	34.3	11.8	4.41	1.80	0.41	47.0 (<8 m)
Zełwążek	0.12	422.2	7.4	3.7	1.81	0.80	0.20	0
Jorzec	0.41	2308.7	11.6	5.5	4.26	1.84	0.30	30.0 (<5 m)

[1] Acc. to Bajkiewicz-Grabowska (1985), average value for two years, 1978–1979.

[2] Acc. to Planter *et al.* (1983).

Hillbricht-Ilkowska (2002a). In general, the 1970s were a little cooler and wetter, whereas the 1990s, especially 1997 and 1998, were drier and warmer. Sampling methods and data processing were the same in both these periods. Analytical procedure (standard methods) is given in Rybak (2002b).

In addition to the analysis of possible long-term changes in each lake separately, also correlations were examined between different trophic parameters for the whole set of data, that is, for all the lakes and years combined, like previously done for different groups of lakes in north-eastern Poland like the Krutynia river in the Masurian Lakeland (Hillbricht-Ilkowska and Kostrzewska-Szlakowska 1996, Hillbricht-Ilkowska *et al.* 1996) and the lakes in the Suwalskie Lakeland (Hillbricht-Ilkowska 1993).

3. RESULTS

3.1. VARIATION IN TP AND TN CONCENTRATION IN LAKE WATERS: DEPENDENCE OF TP CONCENTRATION ON ANNUAL LOADING

No directional year-to-year changes were observed in the spring or summer TP concentration in surface layers (Fig. 2). Each year the values varied in a rather narrow range, most often from 0.03 to 0.10 mg l^{-1} (66% of the cases), but in some years variation was higher. For example, higher values (of the order of 0.5 – 0.7 mg l^{-1}) were noted in downstream lakes (Głębokie, Zelwążek, Jorzec) in spring or summer 1998 (Fig. 2, Table 2). In the mesotrophic Lake Majcz, higher values (about 0.1 mg l^{-1}) were noted in the summer periods of 1996–1998 compared with earlier years, including the 1970s (Fig. 2). This was also the case of over-bottom layers, where TP concentrations ranged between 0.051 and 0.152 mg l^{-1} in different periods of 1996–1998, and between 0.015 and 0.070 for all the earlier years. The values higher than 0.1 mg l^{-1}, and occasionally up to 0.7 mg l^{-1}, were more frequent in summer periods for both surface and over – bottom layers of eutrophic lakes such as Jorzec, Głębokie, and Inulec, as compared with the mesotrophic Lake Majcz. This was also the case in the 1970s (Table 2).

Similarly, no trends were observed for long-term variation in TN concentrations (as the sum of TKN and N-NO_3). Variation in TN concentration noted in different years in both periods and between lakes was high (Table 3). Most values typically fluctuated between 1–2 mg l^{-1} (55% of the cases). Values of 2–4 mg l^{-1} were more frequent in downstream lakes, that is, eutrophic and polluted with sewage (lakes Zełwążek and Jorzec). In these lakes, such values were noted in 47–52% of the cases, whereas in the other lakes, that is, Majcz, Inulec, and Głębokie, in 5, 10, and 20% of the cases, respectively.

Absence of long-term trends in TP and TN concentration is illustrated in Table 4 showing mean values of all measurements (n=8–12) in two successive years, 1992 and 1993 (first column) and three successive years, 1996–1998 (second column). No pairwise comparison was statistically significant; only differences between the mesotrophic Lake Majcz and the remaining lakes, of which two were polluted, were maintained. It should be noted, however, that both TP and TN concentrations in Lake Majcz were higher in 1996–1998 than in earlier years (Table 4).

Large variation in TP and TN concentration gave rise to changes in the N:P weight ratio in surface and over-bottom waters.

The TN:TP ratio by weight for the whole data set (different lakes, layers, and periods of 1992, 1993, 1996, 1997, and 1998) largely varied from below 10:1 to over 50:1, and did not show long-term trends. It was significantly higher (no range overlap) for the spring period (16–31) than for the summer period (12–21), and no significant differences were found between the epilimnion (20–31) and the hypolimnion (13–31). It should be noted that lower values were more frequent in eutrophic, polluted lakes (Głębokie, Zełwążek, Jorzec), especially in their hypolimnion, than in Lakes Majcz and Inulec. Mean values of TN:TP for all the data from 1992 and 1993 (first column) and from 1996–1998 (second column) provide some indication of a probable reduction of this ratio in the upper part of the catchment (Lake Majcz) from about 30 to about 20, whereas it was maintained at a lower level (15–20) in the other lakes (Table 5). According to Smith (1999) the value equal to 17 separates the conditions when the nitrogen or phosphorus respectively becomes the main limiting nutrient.

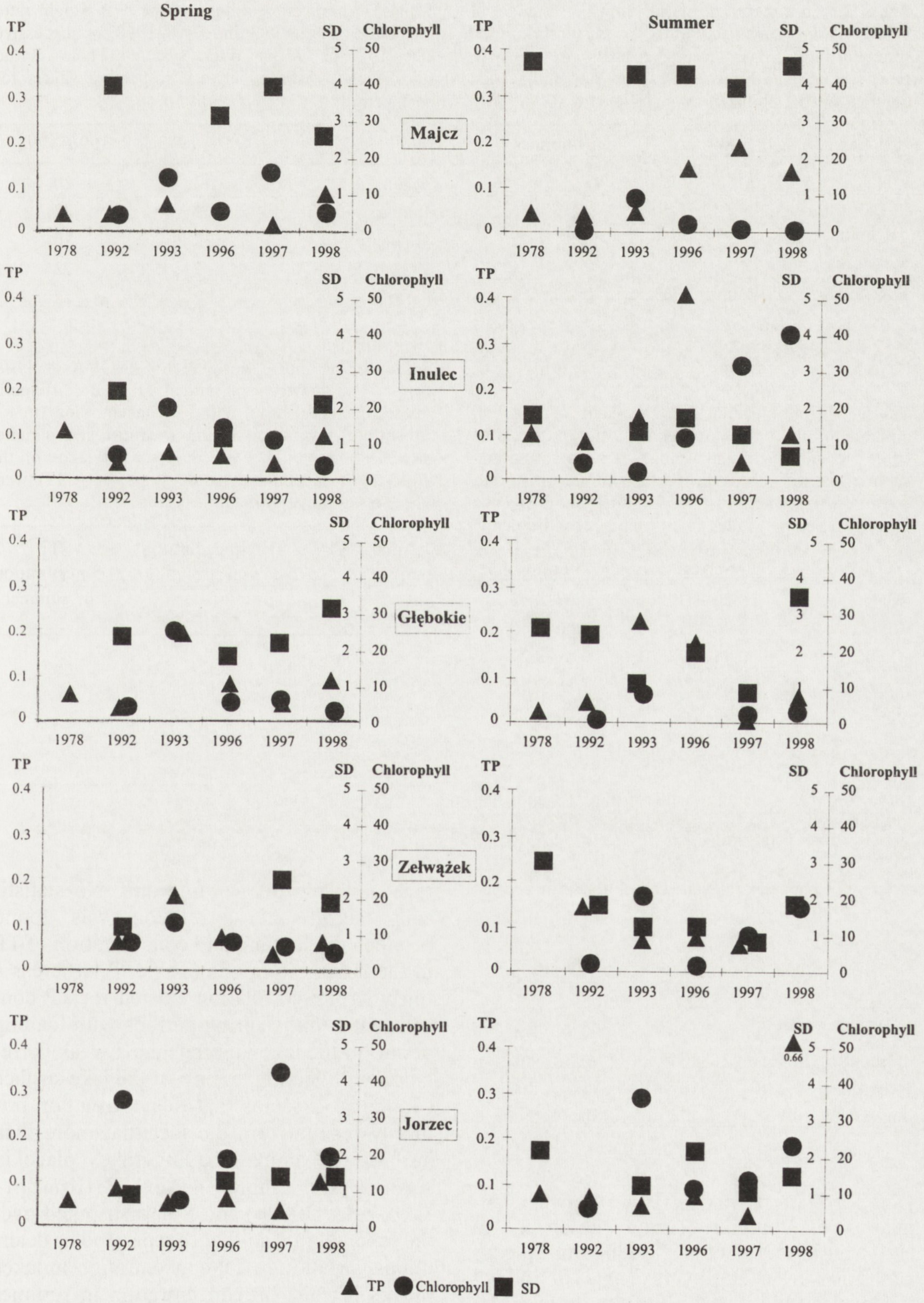

Fig. 2. TP (total phosphorus) concentration (mg l^{-1}), chlorophyll (µg l^{-1}) and Secchi disc readings (SD, m) in the lakes of the Jorka river system (names of successive lakes are given in boxes, see Fig. 1 and Table 1) for spring and summer periods; values for surface layers.

Table 2. Concentration of TP (mg l^{-1}) (range of values for all years[1] and water layes) in spring and summer periods for successive lakes of the Jorka river system. The respective data in first and second column are not statistically significant

Lake	Spring	Summer
Majcz	0.010–0.104	0.030–0.178
Inulec	0.035–0.110	0.038–0.410
Głębokie	0.030–0.210	0.014–0.228
Zełwążek	0.031–0.666	0.051–0.150
Jorzec	0.050–0.500	0.028–0.662

[1] 1978 (acc. to Hillbricht-Ilkowska, Ławacz 1983), 1992, 1993, 1996, 1997, 1998.

Table 3. Concentration of TN (sum of organic, ammonium and nitrate nitrogen) in mg l^{-1} (range of values for all years[1] and water layers) in spring and summer periods for successive lakes of the Jorka rive system. There is no significant difference between relevant values in first and second column

Lake	Spring	Summer
Majcz	0.52–1.37	0.69–2.05
Inulec	0.96–2.74	1.20–2.42
Głębokie	0.85–3.03	0.81–2.29
Zełwążek	0.81–3.79	1.18–2.54
Jorzec	1.06–3.54	1.00–4.15

[1] 1992, 1993, 1996, 1997, 1998.

Table 4. The average values of TP and TN concentration (mg l^{-1}) for period:1992–1993 and period: 1996, 1997, 1998 in successive lakes of the Jorka river system. There is no significant differences between relevant values for both periods

Lake	TP		TN	
	1992–93	1996–98	1992–93	1996–98
Majcz	0.036	0.096	1.115	1.352
Inulec	0.090	0.116	1.800	1.775
Głębokie	0.165	0.104	1.844	1.474
Zełwążek	0.126	0.181	1.825	2.227
Jorzec	0.174	0.178	2.430	2.419

Table 5. The average values of the N:P weight ratio for periods 1992–1993 and 1996–1998 for successive lakes of the Jorka river system. There is no significant difference between respective values for both periods

Lake	1992–1993	1996–1998
Majcz	32	20
Inulec	22	22
Głębokie	15	16
Zełwążek	15	22
Jorzec	22	22

Table 6. The linear correlation (ANOVA analysis) (y = a + x) between the annual TP load differently expressed (see below) and TP concentration (m l^{-1}) in surface layers for spring overturn and summer stratification periods. The data for all lakes of the Jorka river system and study years (n = 19) were used. Ns – non significant

Annual TP load	TP concentration in spring			TP concentration in summer
	R	r^2 (%)	p	
g m^{-3} lake volume	0.60	37	0.008	n.s.
g m^{-2} lake area	0.40	16	0.09	n.s.
kg per lake	n.s.			n.s.

Correlation was analysed between annual TP loading (see Table 2 in Hillbricht-Ilkowska 2002b) and TP concentration in surface layers (Fig. 2) to find out whether variation in this nutrient in lake waters depended on its annual input from all the external sources (river inflow, surface runoff, precipitation). The correlations of loading with the spring or summer TP concentration were calculated for the whole lake, per surface unit, and per volume unit. No statistically significant correlation was found between the loading and concentration of TP in the summer periods (Table 6), whereas a fairly strong correlation existed for TP concentration in the spring periods with loading per m^3 of the lake volume, and a weak correlation with loading per m^2 of the lake surface (Table 6). It seems that this correlation primarily results from the fact that more than half of the annual loading takes place in spring (see Table 4 in Hillbricht-Ilkowska 2002b) and it is distributed over the lake volume so that this parameter determines variation in TP concentration in lakes in this period. TP concentration in summer periods are realized after the period of the highest external loading and because of that their large variation should depend primarily on the rate of TP release from bottom sediments, that is, on internal sources.

For a group of more than 10 lakes of the Krutynia river system (Hillbricht-Ilkowska and Kostrzewska-Szlakowska 1996), and for a group of 20 lakes in the Suwalskie Lakeland (Hillbricht-Ilkowska 1993) the correlations between TP concentration in the surface layer and annual TP loading were also found but only for the summer periods. Presumably, the absence of "summer-time" correlation for lakes of the Jorka river system is a result of large differences in loading between the spring and summer periods; the latter was declining because of reduced discharges in this river in the 1990s (Hillbricht-Ilkowska 2002b). In other lake systems under study, discharges in the summer periods were high, and seasonal differences between spring and summer were smaller than in the lakes of the Jorka river system.

3.2. LONG-TERM VARIATION IN WATER TRANSPARENCY, CHLOROPHYLL CONCENTRATION, AND PHYTOPLANKTON BIOMASS AND COMPOSITION

No clear trends were found in the parameters mentioned above for any lake of the Jorka river system over the study periods (Fig. 2).

In Lake Majcz, the SD visibility of 4 m in the summer period has been maintained since the 1970s (the same value was recorded already in 1950; see Hillbricht-Ilkowska 1999). In the spring period, it decreased to about 3 m. Both these values are typical of mesotrophic lakes (Vollenweider 1989, also Hillbricht-Ilkowska *et al.* 1996). In the eutrophic, shallow Lakes Inulec and Zełwążek and in the eutrophic and polluted Lake Jorzec, water transparency varied without trends between 1 to 2 m in both the spring and the summer periods of all the study years, and without difference between periods 1977–1978 and 1992–1998. In Lake Inulec, similar values were noted already in the 1950s (Hillbricht-Ilkowska 1999). In Lake Głębokie, the values recorded for both phenological periods of 1998 were the highest of all the values observed in this lake, and exceeded 3 m., whereas in earlier years they varied within the range of 1–2.5 m, like in 1977–1978 (Fig. 2). It can be suggested that the increase in water transparency in this lake (to the value approaching the critical value for mesotrophy) was a result of stopping trout aquaculture in 1994 (Penczak *et al.* 1985). Nonetheless, the general conclusion that trends were absent, and the range of variation differed between mesotrophic and eutrophic lakes was valid from year to year. This is illustrated in Table 7 for mean values of water transparency (in metres) in 1992–1993 (first column) and 1996–1998 (second column).

A similar conclusion refers to chlorophyll concentration values that were measured in lakes of the Jorka river system since 1992 (Fig 2, Table 8). In the mesotrophic Lake Majcz, they were below 15 μg l^{-1} all the time, and most often below 10 μg l^{-1} (Fig. 2). Similar values were noted in Lake Głębokie, although in the spring of 1993 (when fish aquaculture was still run), a concentration higher than 30 μg l^{-1} was noted. In the remaining lakes, concentrations higher than 10–20 μg l^{-1} were recorded (typical of eutrophic lakes, Vollenweider 1989) either in spring or in summer. Occasionally, chlorophyll concentration exceeded 40–50 μg l^{-1}, for example, in the polluted Lakes

Table 7. The average values of SD readings (m) for period 1992–1993 and 1996–1998 for successive lakes of the Jorka river system. There is no significant difference between the relevant data for both periods

Lake	1992–1993	1996–1998
Majcz	3.9	3.7
Inulec	1.6	1.5
Głębokie	1.9	2.2
Zełwążek	1.7	1.7
Jorzec	1.2	1.4

Table 8. The average values of chlorophyll a concentration (μg l^{-1}) for periods 1992–1993 and 1996–1998 for successive lakes of the Jorka river system. There is no significant difference between respective values except for Lake Głębokie ($p<0.05$) (*)

Lake	1992–1993	1996–1998
Majcz	7.6	5.4
Inulec	14.0	18.2
Głębokie	10.3*	4.2
Zełwążek	11.9	8.0
Jorzec	21.0	21.3

Zełwążek and Jorzec in 1997. In all the years, data for the summer 1992 were the lowest as compared with later years (Fig. 2). Mean chlorophyll concentrations (Table 8) in 1992–1993 (first column) and in 1996–1998 (second column) did not differ, except for Lake Głębokie, where the decline in chlorophyll concentration in 1996–1998 to the value characteristic of mesotrophic lakes was statistically significant.

No regular variation was observed in the depth of the layer with oxygen concentration below 1 mg l^{-1} in summers of different years (Table 9). The widest layer of hypolimnion (relative to the lake depth) with reduced oxygen content in summer occurred in the polluted Lakes Jorzec and Zełwążek. In deep lakes it varied from year to year, but in the deepest Lake Głębokie, oxygen-free hypolimnion was unusually high in some years, as it reached a depth of 4–5 m. Relatively best oxygen conditions were noted in the largest and shallow Lake Inulec, where oxygen concentration in summer was above 1 mg l^{-1} over at least half of the lake volume (Table 9).

Phytoplankton biomass estimated in surface layers in the spring and summer periods, and the proportion of major algal groups (especially cyanobacteria) represent the most important trophic parameter indicative of the ecological condition of a lake. For 4 out of 5 lakes of the Jorka river system data are available not only from three successive years of 1996–1998 but also from three successive years of 1975–1978, and for Lake Głębokie also from 1979 (Fig. 3). These are, however, data from samples collected at irregular intervals over the year (generally, more often in 1975 and 1976 than in the other years). For this reason, comparison of possible long-term variation and differences among lakes should be based on the analysis of the frequency of occurrence of higher or lower values of biomass, rather than on differences in their absolute values.

In general, the phytoplankton biomass largely varied (Fig. 3). In the mesotrophic Lake Majcz, the values from a few to several mg wet weight l^{-1} were recorded over the study periods, that is, in 1976 and in the 1990s, in both the spring and the summer periods. In the eutrophic Lake Inulec, higher values, ranging between 20–30 mg l^{-1} occurred in the 1970s and the 1990s. A similar situation was observed in the polluted Lakes Zełwążek and Jorzec, where the values of 10–15 mg l^{-1} and 15–50 mg l^{-1}, respectively, occurred in both study periods. Only in Lake Głębokie in the 1990s, that is, after the cessation of trout aquaculture, values higher than 10 mg l^{-1} were not recorded, although they were frequent in the 1970s (Fig. 3). A pre-

Table 9. The depth (m) indicating the upper range of oxygen concentration below 1 mg l^{-1} in summer. Data for successive lakes of the Jorka river system and different years

Lake	Max. depth (m)	1978[1]	1992	1993	1996	1997	1998
Majcz	18.4	8	5	12	7	6	10
Inulec	10.1	8	3	5	4	4	8
Głębokie	34.3	4	8	17	5	16	6
Zełwążek	7.4	5	3	4	3	3	5
Jorzec	11.6	5	5	5	3	3	6

[1] Acc. to Planter *et al.* (1983).

Table 10. The percentage contribution of cyanobacteria and dinoflagellates in total phytroplankton biomass. Data for the 1970s acc. to Spodniewska (1983), and for the 1990s – unpublished data of I. Jasser. Range for spring and summer periods

Lake	1970s		1990s	
	cyanobacteria	dinoflagellates	cyanobacteria	dinoflagellates
Majcz	<1	21	2–7	<79
Inulec	12–24	5–58	1–35	1–82
Głębokie	16–51	21–54	1–14	40–76
Zełwążek	<24	9	1–15	43–73
Jorzec	<5	28	1–2	42–87

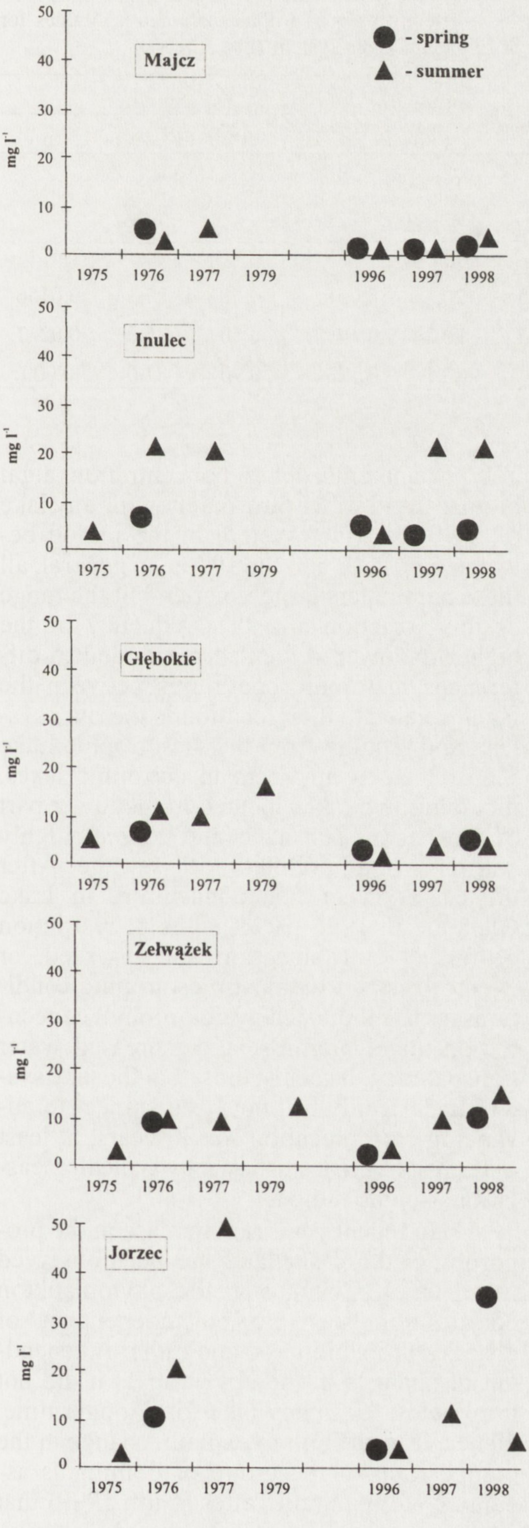

Fig. 3. The biomass of phytoplankton in surface layers in spring (circles) and summer (triangles) of different years for lakes of the Jorka river system (names of lakes are given in boxes, see Fig. 1 and Table 1), (after Spodniewska, 1983 and Jasser, unpubl.).

liminary analysis of the contribution of different groups of phytoplankton in the 1990s (I. Jasser, unpublished data) and its comparison with the published data of Spodniewska (1983) showed that the proportion of dinoflagellates in the phytoplankton was higher than that of cyanobacteria for all lakes in the 1990s. A tentative comparison of ranges for the two algal groups seems to confirm this pattern (Table 10). This is especially the case of polluted downstream lakes. This may provide evidence that the taxonomic composition of algae has changed, and in particular, cyanobacteria retreated, whereas dinoflagellates became dominant. The same long-term shift in phytoplankton composition was observed by Findlay *et al.* (2001).

In sum, based on the analyses of changes in all principal trophic parameters such as TP, TN, and chlorophyll concentration, phytoplankton biomass, and water transparency, it may be concluded that they did not show long-term trends indicative of advancing eutrophication of lakes. This lakes have retained the trophic state observed in previous studies, and the whole lake system maintains strong spatial differences between deep, mesotrophic or weakly eutrophic lakes such as Majcz and Głębokie, and heavily eutrophicated lakes (including those with sewage input) such as Inulec, Zełwążek, and Jorzec. A decrease in chlorophyll concentration and algal biomass, also a slight increase in water transparency in Lake Głębokie in recent years may be signs of the withdrawing of eutrophication as a result of the disappearance of the source of pollution, that is, the trout aquaculture. However, no coherent trends were found in all the four basic trophic indices. Some data are indicative of a decrease in the proportion of cyanobacteria combined with an increase in the proportion of dinoflagellates in the lakes of the Jorka river system in the 1990s compared with 1970s.

3.3. CORRELATIONS AMONG TROPHIC PARAMETERS OF LAKES

No simple, linear correlation was found between TP concentration in surface layers (as independent variable) and the other trophic parameters. This means that TP concentration did not determine variation in chlorophyll content, algal biomass, or water transparency in surface layers during the two periods compared (Table 11). Similarly, in

Table 11. Linear correlations (ANOVA) (y = a + bx) between different pairs of trophic parametres. Values for spring and summer periods of all study years and lakes of the Jorka river system (n = 24)

Parametres		Spring			Summer		
Y	X	R	r^2 (%)	p	R	r^2 (%)	p
SD (m)	TP (mg l^{-1})		n.s.			n.s.	
Chlorophyll (μg l^{-1})	TP (mg l^{-1})		n.s.			n.s.	
Biomass (mg l^{-1})	TP (mg l^{-1})		n.s.			n.s.	
SD (m)	Chlorophyll (μg l^{-1})	–0.45	20.7	0.057	–0.52	27.1	0.0156
SD (m)	Biomass (mg l^{-1})	–0.44	20.2	0.193[1]	–0.50	25.0	0.0247
Chlorophyll	Biomass (mg l^{-1})	0.46	22.1	0.123[1]	0.90	81.0	0.000

[1] marginally significant.

other lake systems no correlation was found (e.g., in the throughflow Krutyńskie lakes, Hillbricht-Ilkowska and Kostrzewska-Szlakowska 1996), or only a weak correlation (Suwalskie lakes, Hillbricht-Ilkowska 1993). In all lake systems, the highest correlation (positive) was found between the content of chlorophyll and algal biomass in summer (Table 11). A little lower but highly significant correlation (negative) occurred between water transparency and chlorophyll in spring, also between water transparency and algal biomass in summer (Table 11). The correlation of the water transparency with biomass, and chlorophyll with biomass in spring in the lakes of the Jorka river system are marginally significant (Table 11). Thus, the lakes of the Jorka river system examined in different years exhibited correlation between chlorophyll content, algal biomass, and water transparency in the summer period, like in other lake systems of the Masurian Lakeland, although for some pairs of these parameters, the correlation seems to be weaker (when water transparency is a dependent variable, Table 11). Similar correlations for the spring period are not significant or they are marginally significant (when biomass is an independent variable) (Table 11), as it was the case of the system of Krutyńskie lakes (Hillbricht-Ilkowska *et al.*1996). For all the lake systems, TP concentration was not correlated or weakly correlated with the other trophic parameters in both phenological periods.

4. CONCLUSIONS AND DISCUSSION

1. No trends were found in long-term variation of basic trophic parameters such as TP, TN, and chlorophyll concentration, algal biomass, and water transparency for any lake of the Jorka river system in the period between the 1970s and the 1990s. In general, all these parameters largely varied but the range of this variation and the frequency of the higher or lower values corresponded to differences in trophic conditions between the lakes, related to their location in the river system, and ranging from the mesotrophic Lake Majcz located upstream to eutrophic lakes, including two lakes located in the lower part of the basin (Zełwążek and Jorzec) highly eutrophic and polluted with sewage. After the cessation of fish aquaculture in Lake Głębokie in 1996–1998, signs of restriction of further eutrophication are observed, or even of return to almost mesotrophic conditions, as it is indicated by chlorophyll concentration, algal biomass, and increased water transparency. It seems, thus, that the lake system under study has not been subject to advancing eutrophication for 20 years, at least in terms of variation shown by typical, measurable trophic indices.

2. In recent years, an increase in the proportion of dinoflagellates has been observed in all lakes. Changes in the phytoplankton composition seem to be independent of changes in its biomass, and rather independent of changes in the N:P ratio as it did not drop below 10 in any lake for a longer time. Hence, it is difficult to explain change in the composition of the group of dominants assuming (for example, after Smith 1999) that cyanobacteria predominate mainly at relatively low N:P, that is, when P concentration is relatively high and that of N relatively low. This situation was not noted over the 20-year period of the study of the lakes of the Jorka river system. It may be possible that the

change in the composition of dominants in the phytoplankton is, for example, a response to short-term fluctuations in concentration of the two nutrients, unnoticeable at monthly sampling intervals. It can be also the response to the decline in TP input from the catchment in the 1990s compared with 1970s (see Hillbricht-Ilkowska 2002b), which did not, however, influence the measurable TP concentration in water and changes in N:P ratio.The same phenomenon that is, the shift in species composition to greater abundance of dinoflagellates (together with large chrysophytes) was found in oligotrophic lakes in the Experimental Lakes Area (ELA) by Findlay *et al.* (2001). The shift was observed as the effect of dry years with longer periods of drought when the nutrient input decreased. This situation was very similar to the one observed in river Jorka lakes. The years 1997 and 1998 were more dry and warm than the proceding ones, the nutrient input and retention were very low and occasionally lakes were functioning as the "source" of nutrients in the river system. The internal loading was likely to dominate over the external loading (Hillbricht-Ilkowska 2002 a, b). Findlay *et al.* (2001) explains the above species succession pointing that *the dinoflagellates are capable of cycling through the deeper, lower light, high nutrient waters presumably to consume bacteria as an alternative to autotrophic production.* This is probably the case of river Jorka lakes; the highest contribution of dinoflagelates was found in downstream polluted lakes. In any case, the replacement of cyanobacteria, that predominated in the 1970s, by dinoflagellates in the group of dominants in the 1990s is a positive change with respect to eutrophication.

3. Simple, linear correlation between the annual TP loading and TP concentration in surface layers during the spring and summer periods and also between the remaining trophic parameters were calculated for the set of all data from the lakes of the Jorka river system. The annual TP loading, of which at least half (and often 80–90%) is loaded to lakes in spring, had a significant effect on TP concentration in lakes over this period, whereas no correlation was found for the summer period. In turn, the TP concentration did not determine (no correlation) variation in the remaining parameters. This is a common situation also in other systems of Masurian lakes (Table 12). Strong or moderate correlations between algal biomass, chlorophyll content, and water transparency, typically higher in summer than in spring, found in the lakes of the Jorka river system are similar to those found in other lake systems, that is, in Krutyńskie (Hillbricht-Ilkowska *et al.* 1996) and Suwalskie (Hillbricht-Ilkowska 1993) lake systems in north-easternn Poland (Table 12).

4. The correlations of trophic indices found for Krutyńskie and Suwalskie lakes in North-eastern Poland (according to sources given above) were compared with the literature data concerning various relationships (regressions) between indices of trophic conditions for different lake systems (e.g., Carlson 1977, Zdanowski 1989, Uchmański and Szeligiewicz 1988) to find out to what extent the latter can be applied to the former. It has been shown that those and the other models with TP concentration in water as an independent variable cannot be applied to the above lake systems. It has also been shown that eutrophication indices such as SD or

Table 12. The correlations between different pairs of trophic parameters in spring and summer periods (values for surface layers) and for three groups of lakes connected with relevant river-lake systems: SUW (Suwalskie lakes, n = 20) (Hillbricht-Ilkowska 1993), KRUT (lakes of river Krutynia, n = 17) (Hillbricht-Ilkowska *et al.* 1996), JORKA lakes (data for 5 lakes but for n =24 periods) (this paper)

		Spring			Summer		
		SUW	KRUT	JORKA	SUW	KRUT	JORKA
TP *versus*:	Chlorophyll	–	*	ns	ns	ns	ns
	SD	–	ns	ns	ns	ns	ns
	Phyt. biomass	–	ns	ns	**	ns	ns
SD *versus:*	Chlorophyll	–	*	**	**	**	**
	Phyt. biomass	–	ns	*	**	**	**
Biomass *versus*:	Chlorophyll	–	ns	*	**	**	**

– lack of data. ns – non significant. *marginally significant (p = 0.1). **significant, p<0.1.

chlorophyll in these lake systems are generally lower than those calculated from these models with measured TP concentration inserted (Hillbricht-Ilkowska *et al.* 1996). The same was found for the five lakes of the Jorka river system – that is no relationship between TP concentration and trophic indices (SD, chlorophyll). The values of the latter should be lower than those calculated from the models with the measured values of TP concentration included. In general, this may imply that in lakes supplied with phosphorus mostly from non-point sources (river inflow, surface runoff, precipitation), a part of TP present in water cannot be assimilated by the phytoplankton (e.g., in the form of mineral and organic complexes derived from the catchment), and as a result the total TP concentration in water is not related to the autochthonous lake production.

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5. SUMMARY

Trophic indices (TN,TP, chlorophyll, algal biomass and composition, oxygen deficit in hypolimnion) were measured in surface and over-bottom layers, of five throughflow lakes (two deep, meso-eutrophic and three shallow eutrophic and polluted) connected with small (15 km) river (the Jorka river system) (Fig. 1, Table 1) in spring and summer periods of several years during the 1970s and the1990s. No directional year-to-year changes were found, nor in spring neither in summer for any of the above parametres (Figs 2, 3, Tables 2, 3, 4, 5, 7, 8, 9). However, there was a significant change in the composition of the algal community: cyanobacteria dominating in the1970s were replaced by dinoflagellates in the 1990s (Table 10). A correlation was found between TP loading to lakes (from river, catchment runoff, precipitation) and in-lake TP concentration in spring when more than 60 % of annual load is supplied with the freshet waters (Table 6). The in-lake TP concentration did not correlate with the variation in other trophic parametres (Table 11). But there were found strong intercorrelations between SD, chlorophyll and algal biomass in summer, and a marginal correlation in spring. The above set of in-lake trophic correlations was found also in other Masurian lake chains supplied mostly with non-point source of nutrients (Table 12).

Lack of visible evidence of eutrophication in the Jorka river lakes seems to indicate that the chains of lakes in mosaic, hilly, postglacial regions are rather resistant to further eutrophication due to the very low input of nutrients supplied mainly from the catchment (so long as the point sources of sewage are eliminated). This situation is also affected by the dry and warm weather which makes that the discharge and nutrient input decreased. The actual trophic differentiation of lakes along the lake chain is mainly the product of the system development in postglacial history and in historical times since XVI century.

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