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BIOGEOCHEMICAL DIVERSITY OF FLUVIAL WATERS AND THEIR EFFECT ON LAKE ECOSYSTEMS IN SUWAŁKI LANDSCAPE PARK (NORTH-EASTERN POLAND)

ABSTRACT: On the basis of data for 29 small stream lakeside watersheds examined in August, spatial diversity of chemical composition of fluvial waters supplying the lakes of Suwałki Landscape Park (north-eastern Poland) has been studied. Differences in chemical composition of waters (consistent for lake waters and the supplying ones) were shown in connection with watersheds of three principal river systems in the Park, i.e. the Szelmentka, Czarna Hańcza, and Szeszupa. The monthly values of areal surface runoff ($\text{kg} \cdot \text{ha}^{-1}$) of phosphorus and nitrogen for summer was estimated and compared with data for Masurian lake watersheds. There was a negative correlation between the flow of streams and phosphorus concentration at the outlet to the lake. Differences in concentrations of some elements significant for phosphorus transformations (Ca, tot-Fe), in phosphorus content in seston and in a dissolved form between fluvial and lake waters were found. This allows to assume that sorption of dissolved phosphorus in lakes is fast (e.g., precipitation in the form of calcium phosphates) and followed by transport to deeper waters on sedimentating seston particles (probably mostly mineral ones).

KEY WORDS: areal surface runoff, phosphorus, eutrophication, Suwałki Landscape Park

1. INTRODUCTION

The Suwałki Landscape Park (SLP) (north-eastern Poland) together with its protection (buffer) zone (Fig. 1) is a fragment of postglacial hilly lakeland with a differentiated relief and high denudations and steep slopes towards lakes (Bajkiewicz-Grabowska 1993). In the Park and its vicinity there is about thirty lakes (mean depth: 1.2–38.7 m, area: 6.5–356.2 ha) including the deepest (in

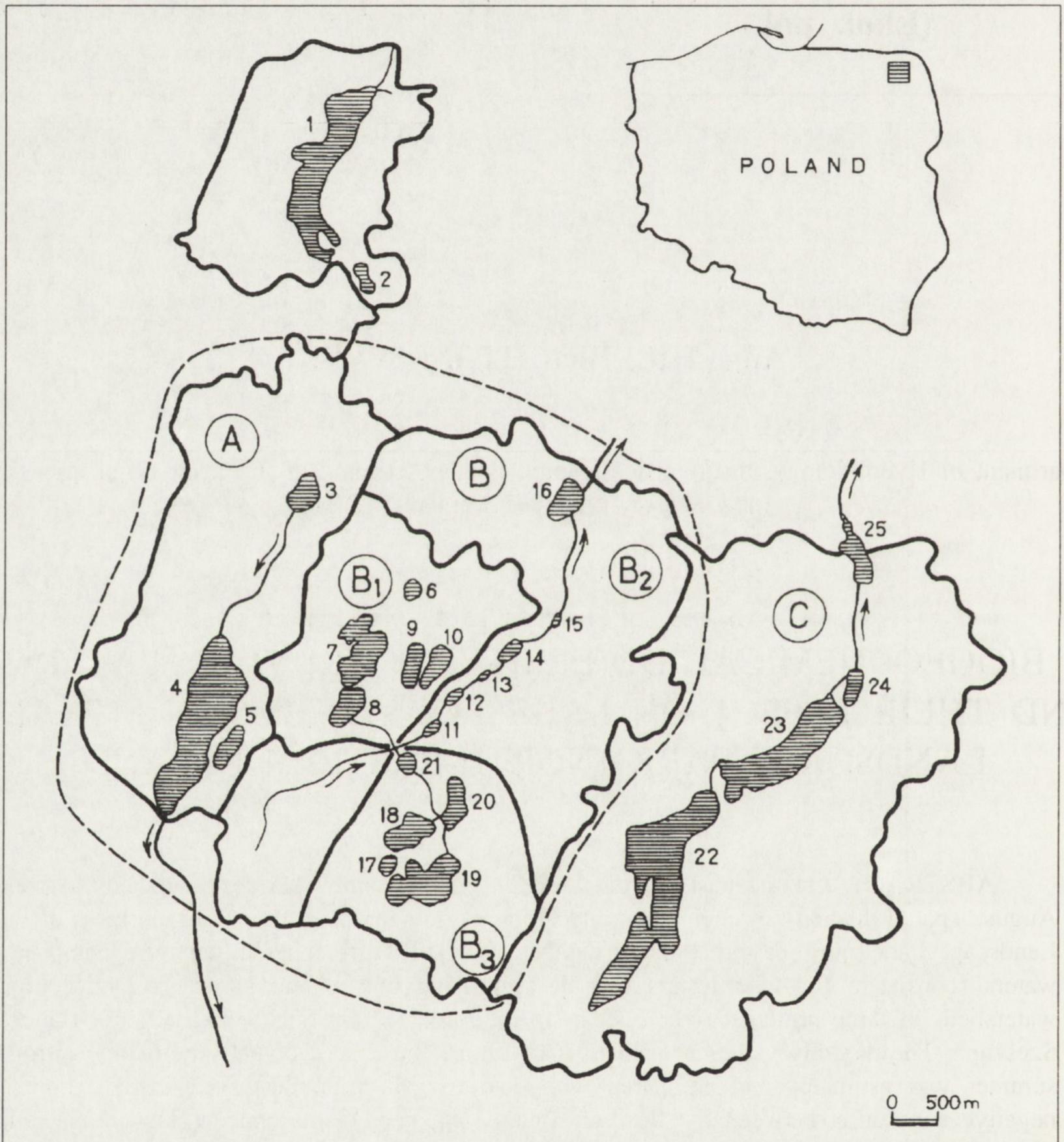


Fig. 1. Scheme of the study area and the Suwałki Landscape Park (SLP), the lakes (1–25) and main river systems (A, B, C)

A – the Czarna Hańcza watershed, B – the Szeszupa watershed including B₁ – watershed of Lakes Jaczno, Kamenduł, Kojle, Perty, B₂ – direct watershed of the river, B₃ – the Szurpiłówka watershed, C – the Szelmentka watershed. Lakes (1–25): 1 – Wiżajny, 2 – Wistuć, 3 – Jegliniszki, 4 – Hańcza, 5 – Boczniew, 6 – Czarne near Smolniki, 7 – Jaczno, 8 – Kamenduł, 9 – Kojle, 10 – Perty, 11 – Gulbin, 12 – Okrągłe, 13 – Krajwelek, 14 – Przechodnie, 15 – Postawełek, 16 – Pobondzie, 17 – Kluczysko, 18 – Jegłówek, 19 – Szurpiły, 20 – Kopane, 21 – Udziejek, 22 – Szelment Wielki, 23 – Szelment Mały, 24 – Iłgieł, 25 – Kupowo. Dotted line – the SLP boundaries together with the surrounding buffer zone (see also Hillbricht-Ilkowska and Wiśniewski, 1993)

Poland), lowland lake Hańcza (max. depth 108.5 m). The lakes are connected with three different river systems in the area (Czarna Hańcza (Fig. 1A), Szeszupa (Fig. 1B) and Szelmentka (Fig. 1C). The area examined is mostly agricultural one, i.e. arable land and pastures constitute about half of the area (ibidem). The two landscape properties, i.e., relief favouring erosion (Smolska 1993) and agricultural utilization may enhance the input of eroded material and nutrients to lakes with the surface

runoff, by means of small streams supplying the lakes either permanently or periodically. This area (Bajkiewicz-Grabowska 1993) shows also a differentiated geological substrate and diverse conditions for outflow (both surface and underground). It may affect the diversity of lakes supply connected with different river watersheds. Therefore the specific questions here are as follows:

1. is there a chemical distinctness (in terms of concentrations and proportions of nutrients and other elements) of water in various small streams and lakes connected with principal rivers of the SLP (i.e. Szeszupa, Szelmentka and Hańcza) which can prove the geochemical diversity of the landscape?

2. is the SLP landscape different in terms of nutrient export rates (P and N) from watersheds similar in size and land use pattern but from other lakelands (e.g., Masurian Lakeland)?

3. is there a relation between chemical composition of stream and river waters and lake waters, and whether chemical differences in waters from different river watersheds affect also those in lake waters?

2. STUDY AREA, MATERIAL, METHODS

The study area consists of watersheds of four groups of lakes, of which three are directly connected with the river systems (Fig. 1, 2). These are: direct watershed of lake Wizajny (part of watershed of the Pissa river in Lithuania) (Fig. 1, lake no. 1) watershed of the Czarna Hańcza river (including lake Hańcza) (Fig. 1A), watershed of the Szeszupa river (Fig. 1B) (together with watershed of its tributary – the Szurpiłówka) (Fig. 1, B₃), where there are several lakes including those indirectly connected with the river (Fig. 1, B₁) and the watershed of Szelmentka river flowing through four lakes (Fig. 1C).

The whole area is a typical hilly lakeland region, utilized for agricultural purposes (i.e., arable land and pastures constitute at least 50% and frequently 90% of the particular watersheds) with differentiated relief, high mean sloping (up to 95, and 42 m · km⁻¹ on the average in lake watersheds) and differentiated conditions of surface runoff (areas without surface runoff represent in some watersheds up to 63% of their area). The area examined is poorly inhabited (mean resident density is 20 persons per km²), has a relatively low pressure of tourism and does not have local sources of industrial emission (Bajkiewicz-Grabowska 1993).

Most of the area examined is within the Suwałki Landscape Park particularly the watersheds of rivers Czarna Hańcza and Szeszupa (Fig. 1 A, B). A number of 29 small (elementary) watersheds were selected (Fig. 2), i.e., drained by small streams up to few kilometres in length and of a surface 0.07–17.33 km² (Table 1) and flowing directly to corresponding lakes (Fig. 2, 1–25). Some longer (few kilometres) river sections between lakes¹ were also studied.

¹Longer sections were chosen as it could be assumed that they do not introduce the waters directly from the above situated lake

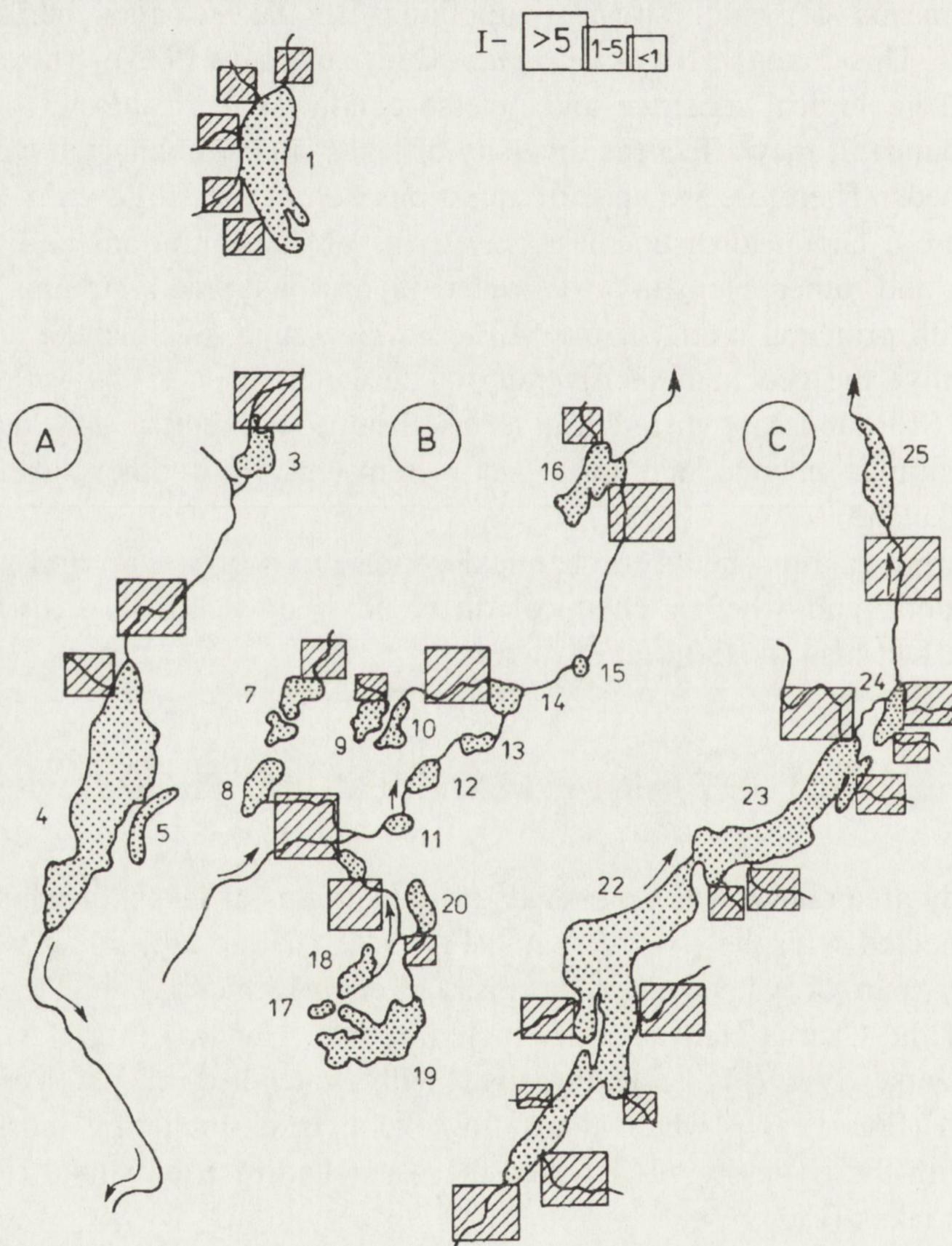


Fig. 2. Localisation of controlled (elementary) watersheds of lakeside streams (hatched area) and lakes
 I – area of watersheds of controlled streams in km^2

For other explanations see Fig. 1

Studies in order to recognize the chemical composition of stream waters from the above elementary watersheds and their load were conducted in the years 1983–1985, in August (successively for consecutive watersheds). In that month, the average multiannual precipitation for the years 1980–1986 acc. to data of Hryniewicz and Przybylska (1993) ranged within 75–85 mm. The rate of discharge from watersheds examined (always measured at the outlet to the lake) scattered broadly: $0.0005\text{--}0.262 \text{ m}^3 \cdot \text{s}^{-1}$ (Table 1), depending on stream length and its development. Generally, stream depths did not exceed 0.5 m (for river sections – 1 m), and 1.5 m in breadth (up to several metres for river section). It has been assumed that the period of investigations (i.e., August) represents sufficiently the relatively typical mid-summer hydrological situation for the whole lakeland, i.e., period formed by

Table 1. Selected properties of elementary lakeside watersheds examined in the Suwałki Landscape Park

River system*	Number of elementary watershes	Watershed area (km ²)	Mean slope (m · km ⁻¹)	Stream density gradient (km · km ⁻²)	Percent of arable land in watershed (plough land, meadows, pastures)	Flow (at the outlet to the lake) in August (m ³ · s ⁻¹)
Szelmentka r.	13	0.7–17.33	14–110	0.51–4.40	51–100	0.001–0.216
Szeszupa r. (with the Szurpiłówka)	8	0.92–11.43	37–92	0.34–3.23	60–92	0.001–0.262
Czarna Hańcza r. (and lake Wizajny)	8	0.14–9.70	17–49	0.25–1.96	80–100	0.0005–0.009

* See Fig. 1.

increased precipitation in summer. Information is provided by seasonal precipitation recorded both for Suwałki Landscape Park (Hryniewicz and Przybylska 1993) and Masurian Landscape Park (Hillbricht-Ilkowska 1989).

At the outlet of streams to the lake, concentrations of the following components were measured: total phosphorus in non-filtered water (TP), in water filtered through GF Whatman filter paper (P dissolved), organic and ammonium nitrogen in non-filtered water (TKN)², in filtered water (KN dissolved), nitrate and nitrite nitrogen, seston (dry weight on filter), concentrations of calcium, magnesium, total iron, potassium and sodium. N-total (TN) was estimated as a sum of TKN and nitrate-nitrite nitrogen and N dissolved (N-diss.) as a sum of KN-diss. and nitrate-nitrite nitrogen. From the differences in phosphorus and nitrogen in filtrated and non-filtrated water, particulate P and N were estimated (in seston suspension), which in turn allowed to estimate the content (%) of these elements in the seston. Also the electrolytic conductivity (EC) was measured. Methods of estimating concentrations of all above mentioned components are described in the paper by Hillbricht-Ilkowska and Wiśniewski (1993).

It was assumed that streams examined and their watersheds, sufficiently represent (considering the land cover, slope, substrate and localisation within the study area) the rate and conditions of surface runoff for the whole SLP lakeland. Because of the lack of significant point-sources (i.e., sewage discharge) the streams may characterize generally the surface runoff in a hilly agricultural landscape. Chemical analysis of

²I.e., nitrogen estimated by Kjeldahl method

stream waters and landscape properties was made for the whole data set and separately for three groups of elementary watersheds connected with principal river catchment basins, i.e., the Czarna Hańcza (including Lake Wizajny), the Szeszupa (with Szurpiłówka watershed) and the Szelmentka as they are natural distinct hydrological and physiographical systems for the study area (Figs 1, 2).

3. RESULTS

3.1. CHEMICAL DIFFERENTIATION OF STREAM WATERS SUPPLYING LAKES FROM ELEMENTARY WATERSHEDS

Preliminary analysis (Hillbricht-Ilkowska 1986) of 26 out of 29 streams examined in this paper has shown a very high variability of concentration and proportion of different phosphorus forms and also of electrolytic conductivity in streams supplying lakes and belonging to different river catchment basins. There is a chemical distinctness of streams supplying lakes belonging to the Szelmentka catchment area in relation to other streams and river systems. Generally, streams of the Szelmentka catchment area are characterised by: higher electrolytic conductivity, greater contribution of dissolved phosphorus forms (P-diss.) and lower percent P – content in seston in relation to all the remaining streams taken together. But these streams (i.e. supplying lakes of the Szelmentka) do not differ statistically as regards the absolute concentration of TP, P-diss., seston and iron. These preliminary results show that there are differences between streams and their elementary watersheds belonging to different river systems on the study area. Thus, further analyses were conducted for the whole pool of streams ($n = 29$) and three selected groups connected with three hydrologically different areas ($n = 8-13$) (Table 1).

The mean values listed for all streams and groups connected with the three rivers (Table 2 and 3, Fig. 3) indicate first of all a great variability (both within and between stream groups) especially of total concentration and of particular forms and proportions of nitrogen and phosphorus compounds and also of seston and iron concentrations. Concentrations of light metals display a much smaller variability inside the groups and in the whole pool of data (Table 3). Due to this variability, the three groups of streams do not differ statistically as regards the concentration of such components as: N-NO₃ (mean for all streams = 0.058 mg · l⁻¹), seston (18.3 mg d.wt. · l⁻¹ on the average), percent content of N in seston (4.6%), weight ratio TN : TP (13.6) and iron concentration (1.19 mg · l⁻¹) (Tables 2, 3, Fig. 2).

Despite great differences among mean values for three groups of streams, the great variability within the group makes them statistically insignificant (Fig. 3). Statistically insignificant differences are also displayed (but due to great similarity of mean values and their variability) by: pH (7–7.5 on the average), percent content of N-diss. in TN which is in all streams about 75–85% and percent content of P-diss. in TP, which is 56–72%, the highest value found in streams of the Szelmentka at the

Table 2. Concentrations and proportions of phosphorus and nitrogen forms – mean values for all streams and their groups* (August)

Component	All streams (n = 29)	Szelmentka river (n = 13)	Szeszupa river (n = 8)	Czarna Hańcza river (+Wizajny lake) (n = 8)
TP (mg · l ⁻¹)	0.113 ± 0.097	0.088 ± 0.034	0.077 ± 0.050	0.191 ± 0.153
TN (mg · l ⁻¹)	1.060 ± 0.553	0.872 ± 0.380	0.886 ± 0.345	1.700 ± 0.664
P diss. (mg · l ⁻¹)	0.060 ± 0.036	0.061 ± 0.027	0.033 ± 0.012	0.083 ± 0.048
KN diss. (mg · l ⁻¹)	0.807 ± 0.541	0.634 ± 0.335	0.606 ± 0.222	1.445 ± 0.743
N-NO ₃ (mg · l ⁻¹)	0.058 ± 0.054	0.045 ± 0.053	0.080 ± 0.045	0.055 ± 0.062
%P diss. in TP	64.4 ± 23.0	71.5 ± 20.8	61.0 ± 23.8	56.3 ± 25.1
%N diss. in TN	78.1 ± 11.8	75.0 ± 10.5	76.4 ± 13.5	86.3 ± 9.9
TN:TP (weight)	13.6 ± 8.2	12.1 ± 7.0	14.7 ± 8.4	15.1 ± 10.8

* See Fig. 1, Table 1

Table 3. Concentrations and indices selected to seston, electrolytic conductivity (EC), pH and light metals – mean values for all streams and their groups* (August)

Component	All streams (n = 25–29)	Szelmentka river (n = 13)	Szeszupa river (n = 6–8)	Czarna Hańcza river (+lake Wizajny) (n = 6–8)
Seston (mg ± l ⁻¹ dry wt.)	18.27 ± 41.68	7.02 ± 4.18	12.8 ± 18.22	41.34 ± 74.25
P in seston (%)	0.55 ± 0.60	0.29 ± 0.36	0.9 ± 0.73	0.63 ± 0.66
N in seston (%)	4.57 ± 4.27	4.18 ± 3.37	3.95 ± 3.5	6.92 ± 7.79
EC (mS · cm ⁻¹)	663 ± 387	981 ± 334	373 ± 56	367 ± 53
pH	7.3 ± 0.4	7.48 ± 0.38	6.95 ± 0.26	7.2 ± 0.28
Fe (mg · l ⁻¹)	1.19 ± 1.09	1.15 ± 1.01	0.97 ± 0.36	1.36 ± 1.44
Ca (mg · l ⁻¹)	65.1 ± 17.8	[95]**[± 20.0]	65.2 ± 23.3	61.3 ± 6.51
Mg (mg · l ⁻¹)	13.7 ± 2.6	[15.1] [± 4.0]	15.8 ± 0.87	11.4 ± 1.67
K (mg · l ⁻¹)	2.05 ± 0.73	[3.7] [± 1.0]	2.17 ± 0.31	1.7 ± 0.89
Na (mg · l ⁻¹)	4.43 ± 1.35	[3.7] [± 1.0]	5.23 ± 0.91	3.7 ± 1.4

* See Fig. 1, Table 1.

**Mean values of 6 inflows to Lake Szelment Wielki (see Fig. 1C) in brackets.

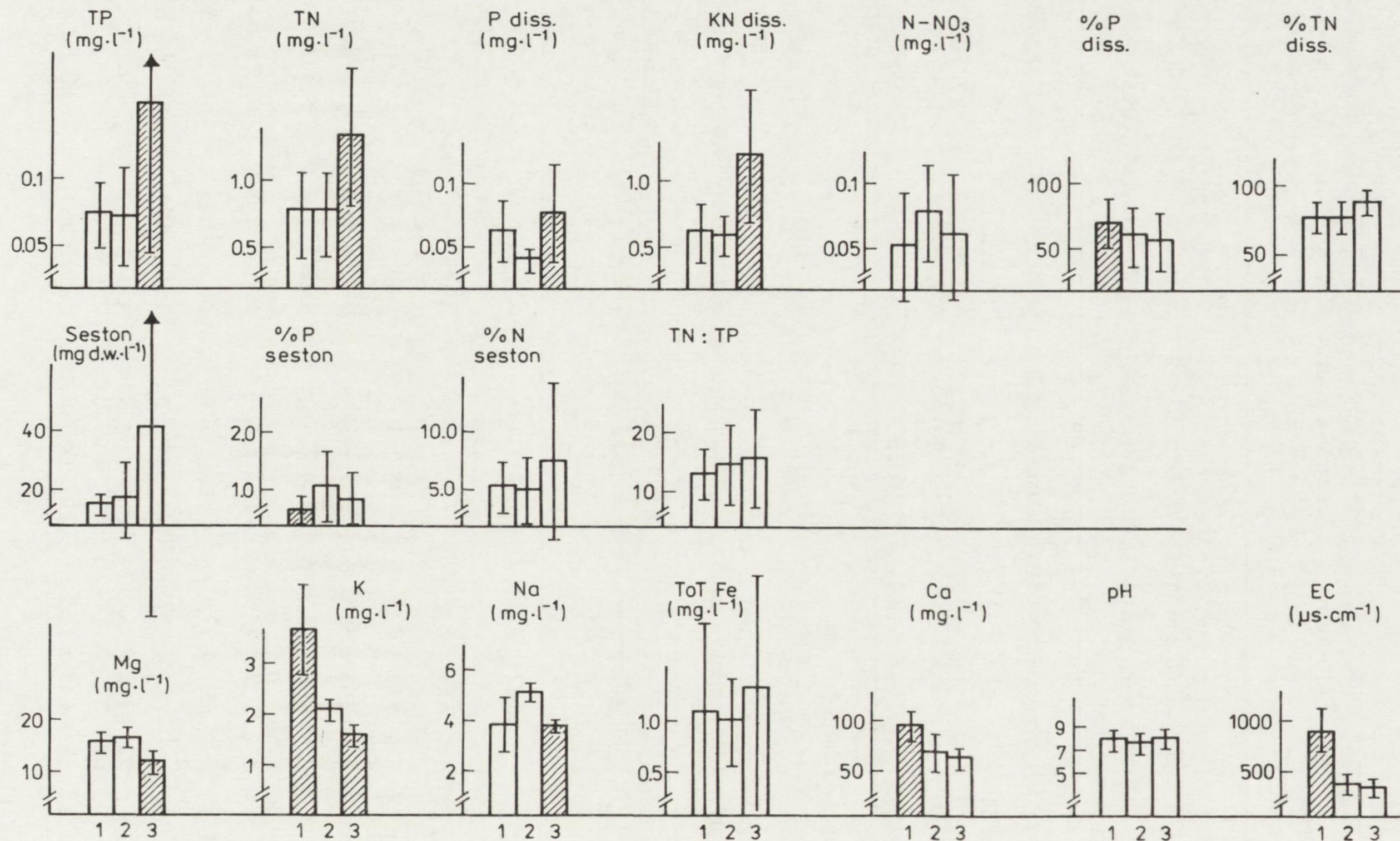


Fig. 3. Mean values (\pm S.D.) of concentrations, forms and proportions of phosphorus and nitrogen, light metals, pH and electrolytic conductivity for groups of streams: 1 – the Szelmentka, 2 – the Szeszupa river, 3 – the Czarna Hańcza (with lake Wizajny)
 Shaded fields – values significantly different ($0.01 < P < 0.05$) from one or both groups of streams

significance limit (Table 3). All the other indices and parameters indicate at least for one group of streams statistically significant differences as compared with the rest. Worth pointing out is the fact that absolute concentration values of TP and P-diss., TN and KN-diss. in streams connected with the Wizajny-Hańcza group of lakes are 1.5–2 higher than in the remaining ones (Table 2, Fig. 2). Few small streams in the direct lake Wizajny watershed in agricultural surroundings are responsible for that. Differences between streams of rivers Szeszupa and Szelmentka are statistically insignificant as regards these components, although streams of the Szelmentka indicate a slightly higher P-diss. concentration in relation to the Szeszupa river and also the highest contribution of this form (but at a significance limit) amongst all groups of streams. But streams of the Szelmentka have the lowest percent content of P in seston as confirmed by results of preliminary analysis (Fig. 3).

As regards light metals, streams in watershed of lake Wizajny and the Hańcza river have the statistically significant lowest Mg, K and Na concentration in relation to other streams and a lower Ca concentration (in relation to one group of streams or one of the lowest) (Fig. 3). Streams supplying the Szelmentka river system apart from high electrolytic conductivity, have also the highest Ca and K concentration, and together with the Szeszupa streams also a high Mg concentration (as related to Wizajny-Hańcza streams) (Fig. 3).

Generally, it can be said that watershed waters of lakes Wizajny and Hańcza have the strongest possible eutrophication effect because of high concentrations of total and dissolved forms of N and P, although their proportions in water and seston and concentrations of nitrate nitrogen display a variability similar to the two other groups of streams. Streams of the Szelmentka with hard waters, of high electrolytic conductivity and Ca concentration, have a lower concentration of total P and N, and a slightly greater contribution of P diss. in TP and lower percent P content in seston.

3.2. ANALYSIS OF NITROGEN AND PHOSPHORUS EXPORT FROM DIFFERENT WATERSHEDS AND ITS RELATION TO WATERSHED PROPERTIES AND FLOW

On the basis of nitrogen and phosphorus concentrations in streams and their flow, the areal surface runoff (ASR) of these elements was estimated in August for the whole month and for area unit (ha) of watershed drained by a given stream. These estimations vary greatly – over three orders of magnitude, and therefore differences between groups of watersheds are not statistically significant (Table 4, Fig. 4). It can be assumed that the estimated areal surface runoff (ASR) roughly characterize hydrological conditions in summer (see Chap. 2). The respective mean values are 0.021 TP and 0.335 TN · month⁻¹ per ha (Table 4). Summer values of ASR-TP and of TP concentrations in SLP region can be compared with results of similar investigations conducted in the Jorka watershed of Mazurian Lakeland (Hillbricht-Ilkowska et al. 1981, Hillbricht-Ilkowska 1988) and in the Krutynia watershed of Masurian Landscape Park (Kufel 1990) (Table 5). On

Table 4. Roughly estimated areal surface runoff (ASR) of nitrogen and phosphorus for the summer period (August) in $\text{kg} \cdot \text{ha}^{-1}$ per month – mean values for all elementary watersheds and their groups*

Component	All watersheds (n = 29)	Szelmentka river (n = 13)	Szeszupa river (+Szelmentka r.) (n = 8)	Czarna Hańcza river (+lake Wizajny) (n = 4–6)
ASR-TP	0.021 ± 0.026	0.020 ± 0.021	0.031 ± 0.038	0.009 ± 0.016
ASR-TN	0.335 ± 0.579	0.223 ± 0.237	0.644 ± 0.937	0.080 ± 0.119

* See Fig. 1, Table 1

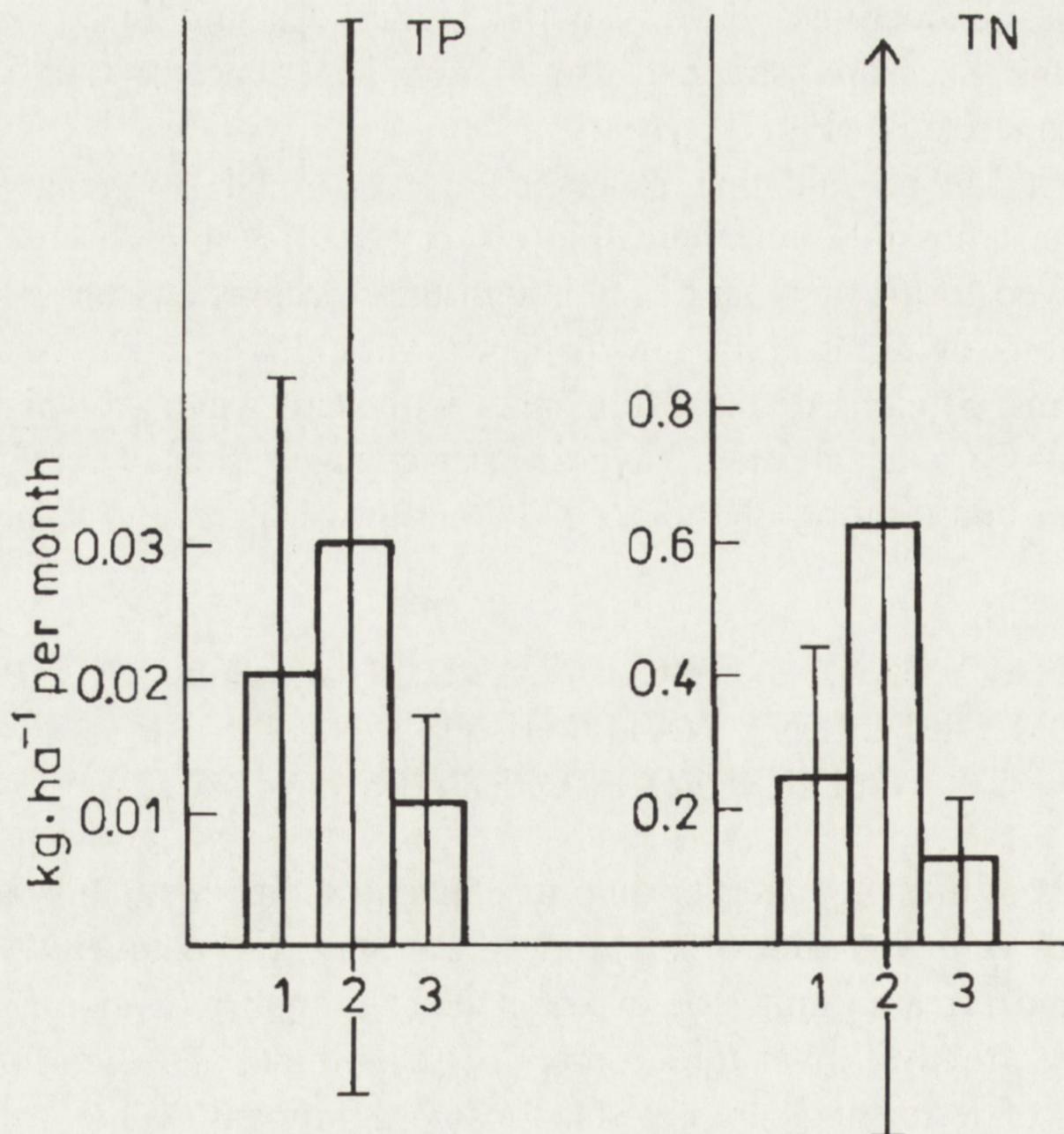


Fig. 4. Mean (\pm S.D.) areal surface runoff ASR in $\text{kg} \cdot \text{ha}^{-1}$ per month (August) of total phosphorus (TP) and nitrogen (TN) for groups of streams successively: 1 – the Szelmentka, 2 – the Szeszupa, 3 – the Czarna Hańcza (see Fig. 1 and 2)

both these areas, being also fragments of hilly lakeland and utilized by agriculture (although of a lower slope, Table 5) studies were conducted on TP concentration and discharge for a number of small streams draining waters from comparable in size elementary watersheds and running directly to particular lakes. These streams were not polluted by point-sources, except two streams distinguished in the Jorka watershed (Table 5). But all compared streams drain areas with a prevalence of arable land (ploughed grounds, cultivated meadows and pastures). The bottom range for all three areas compared contains data for few small non-polluted watersheds and of a low slope in the Jorka watershed, whereas in the upper range of all data – two polluted watersheds (breeding farms, urban areas) of the already mentioned Jorka river are located (Table 5).

This compilation of data allows to estimate that in summer, when the mean multiannual precipitation is about $75\text{--}85 \text{ mm} \cdot \text{month}^{-1}$, the areal surface runoff (ASR) of total phosphorus from small stream watersheds – (the discharge below $0.2 \text{ m}^3 \cdot \text{s}^{-1}$) usually fluctuates between 0.001 (probably for fragments of landscape of a low sloping, and thus lower erosion) and $0.07\text{--}0.1 \text{ kg TP} \cdot \text{ha}^{-1}$ per month for areas utilized by agriculture (farms, pastures, villages) and/or of a greater erosion due to the high sloping conditions (Table 5).

The preliminary analysis (Hillbricht-Ilkowska 1988), in which the values of ASR-TP in the Jorka watershed and in SLP watersheds, were compared, indicate, that higher ASR-TP values for Suwałki watersheds, can be due to conditions enhancing erosion. Including Kufel's (1990) data on the analysis of small elementary watersheds in the Krutynia catchment basin seems to confirm this suggestion (Table 5): values of slope for the Krutynia watersheds are greater than for the Jorka watershed – also their ASR-TP values are higher for June and September (Table 5). A similar comparison of TP concentration shows that mean mid-summer values for all compared streams is usually below $0.1 \text{ mg} \cdot \text{l}^{-1}$, and rarely below $0.2 \text{ mg} \cdot \text{l}^{-1}$, whereas in streams from areas with intensive agriculture (breeding farms, villages) it may reach $0.5 \text{ mg} \cdot \text{l}^{-1}$. Values of $0.2\text{--}0.5 \text{ mg} \cdot \text{l}^{-1}$ have to be considered as highly eutrophic.

The analysis of relations for 29 SLP elementary watersheds between concentration and load of TP and TN and their dissolved forms (including N-NO₃) and watershed properties increasing the export of these elements (percent of arable land, slope, stream density gradient) or decreasing it (percent of forest and wetlands) did not show statistically significant correlations. It seems to be caused first of all by small differentiation of watersheds examined as regards these properties (arable land generally cover at least 50%), necessary for this kind of analysis. Also the relation found by Kufel (1990) for 11 watersheds of the Krutynia was not confirmed, i.e., negative correlation between the load of dissolved forms of nitrogen and the percent area of wetlands and forests in the watershed. However, this author also did not find any relation between the load of TP and P diss. and the above land cover indices. No correlation was also found in this study between the concentration of different nitrogen forms and the flow rate. However, a negative

Table 5. Comparison of concentration and areal surface runoff (ASR) of total phosphorus (TP) from different groups of small elementary watersheds of the Suwałki and Masurian Lakelands – range of values for watersheds examined in summer months

Region, river, number of watersheds (n)	Area (km ²)	Flow (m ³ · s ⁻¹)	Arable land (%)	Slope (m · km ⁻¹)	Concentration (mg · l ⁻¹)	ASR (kg · ha ⁻¹ per month)
Suwałki*:						
Szelmentka r. (n = 13)	0.07–17.3	0.001–0.216	51–100	14–100	0.036–0.168	0.002–0.064
Szeszupa r. (+Szurpiłówka) (n = 8)	0.92–11.43	0.001–0.262	60–92	37–92	0.032–0.152	0.001–0.11
Czarna Hańcza r. (n = 7)	0.14–9.20	0.0005–0.009	80–100	17–50	0.056–0.464	0.0005–0.043
Mazurian:						
Jorka river non-polluted watersheds** (n = 7)	0.3–2.3	0.05–0.020	>50	4–15	0.02–0.10	0.001–0.007
Jorka river polluted watersheds** (n = 2)	0.3–13.3	0.005–0.150	>50	5–10	0.30–0.50	0.05–0.07
Krutynia r.*** (n = 11)	1.06–11.62	0.002–0.070	>50	6–28****	0.035–0.180*** 0.035–0.120	0.002–0.06*** 0.002–0.052

* Data of the present paper.

** Hillbricht-Ilkowska (1988) modified.

*** Kufel (1990), data for June and September, recalculated.

****acc. to Bajkiewicz-Grabowska (Hillbricht-Ilkowska 1989).

correlation was found between the flow and TP and P diss. concentration expressed by log-log regression (Table 6). With the increasing flow rate of streams from 0.0001 to $0.25 \text{ m}^3 \cdot \text{s}^{-1}$, the concentration of total and dissolved phosphorus decreases. This relation found in 28 streams of SLP area has been also stated for the Jorka streams varying in length and flow (comparable with SLP streams) and for various stations of a single stream (Hillbricht-Ilkowska 1988).

Table 6. Statistical analysis (ANOVA) of regression ($y = a+bx$) log TP ($\text{mg} \cdot \text{l}^{-1}$) (A) and log P diss. ($\text{mg} \cdot \text{l}^{-1}$) (B) and log Q (flow in $\text{m}^2 \cdot \text{s}^{-1}$) for controlled lakeside streams of Suwałki Landscape Park

	Intercept (s.e.)	Slope (s.e.)	n	r^2 (%)	P	r
A	-3.031 (0.277)	-0.122 (0.049)	29	18.2	0.021	-0.43
B	-3.495 (0.247)	-0.106 (0.045)	28	17.7	0.026	-0.42

This shows that in small streams of a generally low flow, with the increasing flow, probably a sorption of phosphorus occurs on transported particles, which in turn is sedimentated in the stream bed or absorbed by stream vegetation. However, it should be pointed out that such a phenomenon may occur in periods of stable and moderate flow. Under conditions of rapid water rise (e.g., following storms, freshets) phosphorus accumulated in the stream bed sediments may become mechanically washedout and carried into the lake.

3.3. RELATION BETWEEN THE CHEMICAL COMPOSITION OF LAKE WATERS AND WATERS OF SURFACE RUNOFF FROM DIRECT LAKE WATERSHED

It is shown in Chapter 3.1. that small watersheds of lakeside streams connected with three main river systems in the region: Szelmentka, Szeszupa and Czarna Hańcza, display in summer months statistically significant differences as regards mean concentration of some components.

Streams of the Szelmentka catchment basin are characterized by: high conductivity, higher Ca, K and Mg concentrations, lower TP and TN concentration but by a greater absolute and percent content of P-diss. in TP and by lower percent P content in seston. Streams of Lake Wizajny and the Czarna Hańcza watershed show: a high TP and TN concentration (small streams supplying Lake Wizajny decide about it) and lower Mg, K and Ca concentrations. Streams of the Szeszupa system have the concentration of nutrients similar to the Szelmentka streams, but display a much lower conductivity and Ca and K concentration, a slightly higher Mg and Na concentration and higher P % content in the seston. These results point to a distinct chemical character of fluvial waters running off direct lakes watersheds connected

with three main hydrographical systems of the study region. Therefore, it can be expected that the waters of lakes have also a consistently distinct chemical composition. This consistency of chemical nature, common for waters of streams and lakes of a given watershed do not mean however, that chemical composition of waters supplying the given lake and in the lake is identical. The difference between chemical composition of the streams supplying the given lake (and especially the river flowing into it) and its surface waters is sometimes quite considerable. Hillbricht-Ilkowska (1990) has observed that in some mesotrophic lakes of SLP in summer there are significant differences in concentration of certain compounds (Ca, Mg, tot-Fe, conductivity) in river waters inflowing and in surface lake waters, indicating "losses" (dilution and/or sorption) of these compounds in the lake.

Quite considerable may be also the differences in relative amounts of different forms of nutrients in surface waters of lake and river supplying it such as: percent content of dissolved P in total P, weight ratio TN : TP or percent content of P in the seston. This difference allows to conclude about the direction of transformation of N and P load reaching the lake with the water of supplying river or stream. Thus, an appropriate analysis was carried out using the data (August) for river or stream inflows to the lakes (23 stations altogether) and data on chemical composition of surface (epilimnetic) waters of 25 lakes in the study area. The morphometric and trophic characteristics of these lakes and their localisation in river system (i.e., Szelmentka, Czarna Hańcza and Szeszupa, and their tributaries) are given by Hillbricht-Ilkowska and Wiśniewski (1993), see also Figs. 1, 2.

Comparison of data (Fig. 5)³⁾ on concentration of light metals in surface waters of lakes versus their fluvial supply has a double aim: to indicate possible differences between particular watersheds consistent for the river and lakes it supplies and to show the difference between concentrations of these components in lake waters and waters of river supply. The most consistent changes in the majority of compared components are observed for the Szelmentka and its lakes (Fig. 5, watershed I). Both lake waters and river waters of this system have a very high conductivity, the highest Ca, K and tot-Fe concentration and high (although not the highest one) Mg concentration. Simultaneously, some of these components (i.e., conductivity, Ca and K) have lower concentrations in lake than in river, pointing thus to their dilution and/or precipitation. A similar trend is observed in the case of lakes connected with the Czarna Hańcza and Lake Wizajny (Fig. 5, watershed II). Both streams and lakes of this system have the lowest conductivity, lowest Ca, Mg and Na concentration and one of the lowest (although not the lowest) tot-Fe and K concentrations. Similarly as lakes of the Szelmentka, they tend to have the lowest concentrations of all components (except Na) in lake waters as compared with the river.

Other lakes, i.e., those connected directly with the Szeszupa (Fig. 5, watershed IV) and its tributary Szurpiłówka (watershed V) have similar concentrations of

³⁾Different number of lakes in Figures 5 and 6 is due to incomplete data for some lakes

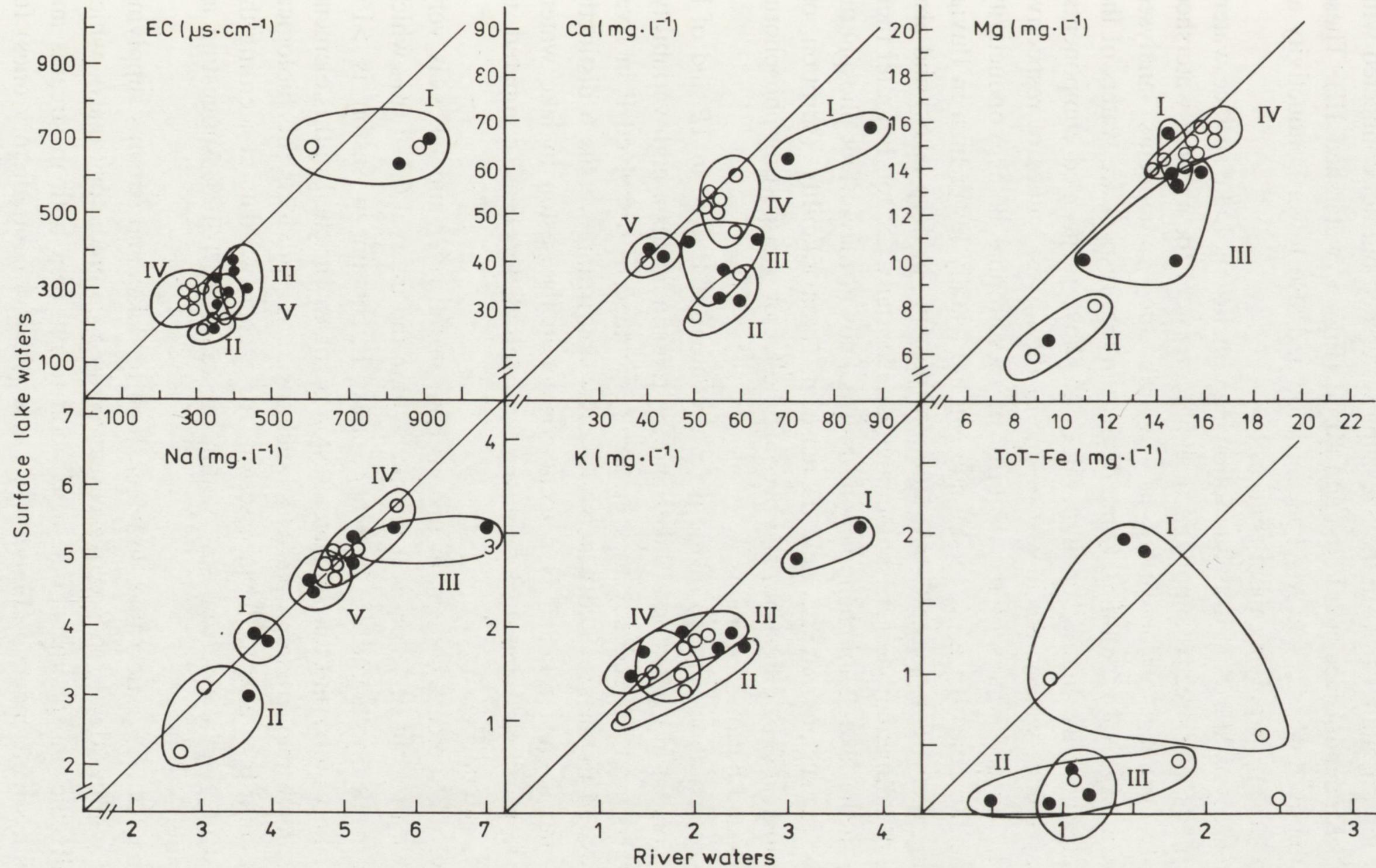


Fig. 5. Concentration of selected components (Ca, Mg, Na, K, tot-Fe) and electrolytic conductivity (EC) in waters of river supply vs in surface lake waters of Suwałki Landscape Park (August) for groups of lakes from different watersheds (see Figs. 1, 2)
 I – Szelmentka river, II – Czarna Hańcza river and Lake Wiżajny, III – watershed of lakes Kamendul, Jaczno, Kojle and Perty, IV – Szeszupa river (without watershed of lakes Kamendul, Jaczno, Kojle and Perty and the Szurpiłowka watershed), V – the Szurpiłowka. Description of lakes and their watersheds in Hillbricht-Ilkowska and Wiśniewski (1993). Dark points – mesotrophic lakes

analysed components (sometimes highly convergent) as well as intermediate between two above mentioned groups of lakes. However, an exception are four mesotrophic lakes of a very low through – flow in the Szeszupa watershed but not connected with it directly, i.e., Kamenduł, Jaczno, Perty and Kojle (Fig. 5, watershed III). These lakes have distinctly lower Ca and Mg concentration and also lower conductivity as compared with streams supplying them (Fig. 5).

The above analysis allows to draw the following conclusion. Lake surface waters with those of rivers and streams supplying it show consistent for a given watershed distinctness of chemical composition as regards the components analysed (conductivity, Ca, Mg, Na, K, tot-Fe). Quite distinct in that respect are waters of the Szelmentka watershed (the highest or high values of above mentioned components) and the Czarna Hańcza waters (the lowest or one of the lowest values of respective components). In surface waters of the majority of mesotrophic lakes, conductivity values and concentrations of Ca, K, tot-Fe and Mg are usually lower than in fluvial waters supplying them. This suggests both dilution (possible in deep lakes) and also precipitation and sedimentation of these compounds (especially Ca, tot-Fe) after their transformation in the lake. This phenomenon, as it is known, may affect phosphorus transformations in surface layers, i.e., decrease its bioavailability (sorption on products of biological decalcification) and become the factor transporting phosphorus to deeper layers and bottom sediments.

Graphical presentation (Fig. 6) of the percent content of P diss. in TP and of P and N percent content in the seston of lakes and the river indicates a high variability. However, there is a slight tendency to a greater percentage of dissolved P in river waters as compared to surface lake waters (10 cases confirming versus 6 distinctly contradictory) and a greater P and N percent content in the seston in lake waters (10–12 cases confirming against 3–5 distinctly contradictory) as compared to supplying river waters (Fig. 6).

Variability of P percent content in seston, both in the river and lakes, is very high (0.1–5.0%). In 7 out of 18 cases it remains within the interval 0.1–1.0%, which suggests an organically bound P. In other cases, P contain in seston is >1% (especially in lake waters) and this indicates seston particles enriched in this element. It can be assumed that mineral particles such as, e.g., products of biological decalcification contribute also to the lake seston. All except two data concerning the percent content of N in the seston, stay within the range of 1–10% suggesting an organically bound N (Fig. 6).

Most of the TN : TP ratio values in water, both for lakes and streams supplying them, remains within 20–40 (15 positive cases versus 5 contradictory ones), which proves generally the phosphorus deficit in relation to nitrogen both in streams and lakes. There is a slight tendency (11 positive cases versus 8 contradictory ones) for this ratio to increase in lake waters as compared with waters supplied by rivers (Fig. 6). These tendencies of changes of indices related to N and P transformation in the water and seston of lakes in comparison to river waters, allow to draw a cautious (as particular relations in Fig. 6 are poorly documented) but consistent conclusion.

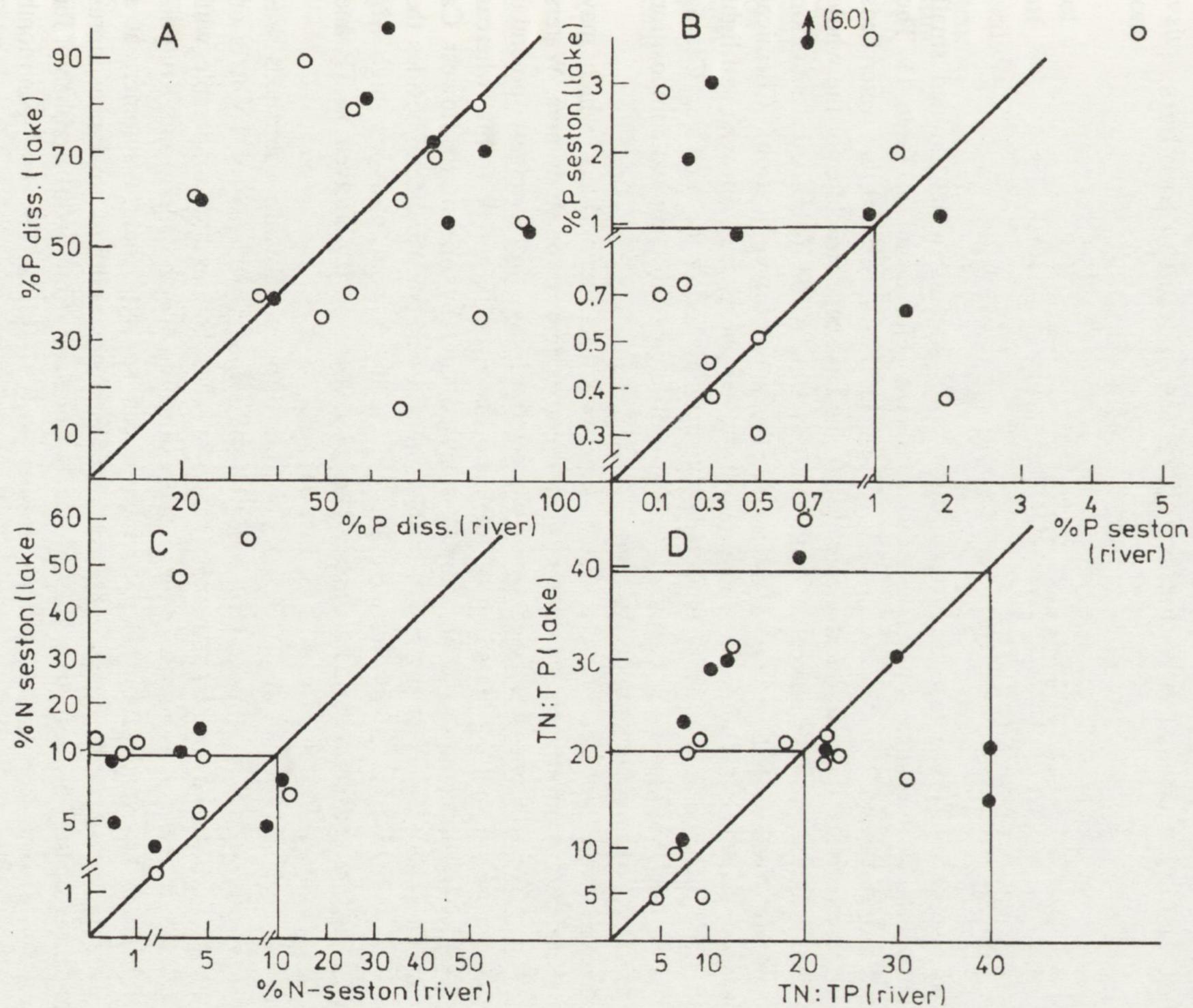


Fig. 6. Comparison of relative amounts of phosphorus and nitrogen in waters of river supply vs. in surface waters of Suwałki Landscape Park lakes (August)

A – percent content of P diss. in TP, B – percent content of P in seston, C – percent content of N in seston, D – weight ratio TN : TP, dark points – mesotrophic lakes

In lake surface waters, the uptake of dissolved phosphorus carried by the river takes place followed by transformation into sestonic form (seston becomes enriched with this element). But in some lakes, judging by all values of percent content in seston there is also sorption on the mid-lake suspension of inorganic particles. This is frequently accompanied by an increase of TN : TP ratio in lake waters, i.e., an increase of relative deficit of phosphorus in relation to nitrogen is observed. These tendencies are obvious when analysing the whole group of SLP lakes (Fig. 6). The group of several mesotrophic lakes in Figure 6 does not have a specific place, and therefore does not display a consistently distinct character in relation to others.

4. SUMMARY

In August, in the years 1983–1985, chemical composition of 29 streams, which drained small (area: 0.07–17.33 km²) lakeside elementary watersheds was analysed (Fig. 1 and 2, Table 1). The discharge at the outlet to lake ranged 0.0005–0.262 m³ · s⁻¹ (Table 1). It was assumed that watersheds examined and the period of investigation sufficiently characterize the landscape structure for the whole area (differentiated relief, high slopes, prevalence of arable land) as well as the hydrological situation typical for summer in the north-eastern region (effect of higher summer precipitation). Chemical composition was analysed, i.e., the concentrations of total and dissolved phosphorus, nitrogen and light metals for all streams and also for their groups connected with main rivers on the area i.e.: Czarna Hańcza, Szeszupa and Szelmentka (Figs 1, 2). Analysed were also differences in chemical composition of lake surface waters, and stream waters supplying them.

Consistent differences were recorded between waters supplying three main rivers, which may prove a strong spatial differentiation of chemical nature of the runoff waters in the study area. Waters of Lake Wizajny and Lake Hańcza watersheds are characterized by the strongest potential eutrophication effect, because of high concentration of total and dissolved N and P forms, whereas of a lowest Mg, K and Na concentration of all streams analysed, and by one of the lowest Ca concentration. On the other hand, waters of streams of the Szelmentka watershed indicate, besides the highest and generally very high conductivity, also the highest Ca and K concentrations, high Mg concentration, lower P and N concentrations, but higher percent content of P dissolved in TP and lower percent content of P in the seston (Tables 2, 3, Fig. 3).

Monthly values of areal surface runoff of TP and TN from different lakeside watersheds was estimated for August. For TP it is 0.021 (range 0.01–0.03) on the average, whereas for TN it is on the average 0.335 (range 0.2–0.6) kg · ha⁻¹ per month (Table 4). These values are comparable with similar ones (i.e., calculated also for a summer month) and estimating for the Jorka and Krutynia watersheds of the Mazurian Lakeland (Table 4). Generally it can be said, that in summer, at a multiannual mean monthly precipitation about 75–85 mm, areal surface runoff of total phosphorus from small lakeside watersheds (flow less than 0.2 m³ · s⁻¹) fluctuates from 0.001 (probably for fragments of landscape of a small slope and thus lower erosion) to 0.07–0.1 kg TP · ha⁻¹ per month for areas with intensive agriculture (breeding farms, pastures, villages) and/or of a greater erosion because of the steep slopes. TP concentrations in summer for this type of streams are usually below 0.1 mg · l⁻¹, rarely they reach 0.2 mg · l⁻¹, whereas in streams from areas with intensive agriculture they may reach 0.5 mg · l⁻¹. Values within 0.2–0.5 mg · l⁻¹ should be considered as highly eutrophic (Table 5).

No relations were observed between the concentration and load of phosphorus exported in summer from lakeside watersheds and such watershed properties as contribution of arable land, stream density gradient or mean slope. However, a weak negative correlation was found between the flow and concentration of total and dissolved phosphorus expressed as log–log regression (Table 6). According to it, as streams develop and their discharge increases (within 0.001–0.25 m³ · s⁻¹),

phosphorus concentration, both total and dissolved, decreases. A similar relationship has been also observed for the Jorka streams on Masurian Lakeland. A conclusion may be drawn, that in small streams of a generally low discharge, with their development and increase of discharge, phosphorus sorption probably takes place on transported particles, which are then sedimentated in the stream bed or absorbed by bank and in-stream vegetation. However, this may occur under conditions of relatively stable and moderate flow.

It has been shown that surface waters of lakes with those of rivers and streams supplying them, show consistently distinct chemical composition in a given watershed as regards the analyzed components such as: Ca, Mg, N, Na, K, tot-Fe and electrolytic conductivity (Fig. 5). The waters of the Szelmentka watershed are distinguished, where both lakes and streams have the highest or high values, whereas the waters of lakes and streams of the Carna Hańcza watershed show the lowest or one of the lowest values of these components.

For many of the 25 lakes, the majority of which are mesotrophic, much lower concentrations of Ca, K, Mg, tot-Fe and conductivity in lake (surface) waters were observed as related to waters of their river supply. This suggests both dilution (which can take place in deep lakes) and sedimentation of these compounds (especially Ca and tot-Fe). The latter seems to explain the tendency to higher percent content of P and N in seston, smaller content of dissolved forms in total amount, and higher TN : TP ratio in surface waters as compared with waters of their river supply (Fig. 6).

A following mechanism could be expected: in lake supplied mostly by streams, uptake of dissolved phosphorus transported by the stream takes place, then it passes into seston (thus the enrichment of seston in this element takes place) both by means of biological assimilation and sorption on inorganic particles flowing into the lake (Ca and Fe compounds). These particles sedimentate quickly, resulting in phosphorus transport to deeper waters, as it is shown by an increase of relative P deficit in lake waters as related to river waters (higher TN : TP ratio) and a decrease in concentration of mineral compounds (Ca, Fe) engaged in phosphorus sorption.

5. POLISH SUMMARY

W sierpniu w latach 1983–1985 analizowano skład chemiczny 29 cieków odprowadzających wody z niewielkich (powierzchnia od 0,07 do 17,33 km²) zlewni przyjeziornych bezpośrednio do odpowiednich jezior (rys. 1, 2, tab. 1), których przepływ w ujściu do jeziora mieścił się w granicach 0,0005–0,262 m³ · s⁻¹ (tab. 1). Przyjęto, że badane zlewnie, i okresy badań charakteryzują dostatecznie zarówno strukturę krajobrazu właściwą całości badanego obszaru (zróżnicowana rzeźba, wysokie deniwelacje, przewaga użytków rolnych), jak i sytuację hydrologiczną typową dla okresu letniego północno-wschodniego rejonu (efekt podwyższonych opadów letnich). Analizowano skład chemiczny tj. zawartość zarówno fosforu i azotu oraz wybranych metali lekkich dla wszystkich cieków, a także grup powiązanych z głównymi rzekami obszaru badań: Czarna Hańcza, Szeszupa i Szelmentka (rys. 1, 2). Ponadto zanalizowano różnice pomiędzy składem chemicznym wód powierzchniowych jezior i wód rzecznych.

Stwierdzono spójne różnice pomiędzy wodami zasilania trzech głównych rzek obszaru, które mogą dowodzić silnego przestrzennego zróżnicowania składu chemicznego w spływie powierzchniowym badanego obszaru. Wody zlewni jezior Wizajny i Hańcza odznaczają się najsilniejszym potencjalnym wpływem eutrofizującym ze względu na wysokie stężenie form ogólnej i rozpuszczonej N i P, natomiast najniższą zawartością Mg, K i Na w stosunku do wszystkich analizowanych cieków, oraz jedną z niższych zawartości Ca. Z kolei wody cieków zlewni Szelmentki wykazują obok najwyższego i ogólnie bardzo wysokiego przewodnictwa, również najwyższą zawartość Ca i K i wysoką zawartość Mg, niższe stężenia P i N, ale zwiększoną procentową zawartość P rozp. i mniejszą zawartość P w sestonie (rys. 3, tab. 2 i 3).

W sierpniu oceniono wielkość jednostkowego spływu obszarowego TP i TN z różnych zlewni przyjeziornych. Dla TP wynosi on średnio 0,021 (zakres 0,01–0,03) zaś dla TN średnio 0,335

(zakres 0,2–0,6) $\text{kg} \cdot \text{ha}^{-1}$ na 1 miesiąc (tab. 4). Wartości te są porównywalne dla analogicznych (tzn. obliczanych dla miesiąca letniego), ocenionych dla zlewni rzeki Jorki i rzeki Krutyni na Pojezierzu Mazurskim (tab. 4). Ogólnie można powiedzieć, że w okresach letnich przy wieloletniej średniej opadów rzędu 75–85 mm w ciągu miesiąca, jednostkowy spływ powierzchniowy fosforu ogólnego z małych zlewni przyjeziornych (o przepływie poniżej $0,2 \text{ m}^3 \cdot \text{s}^{-1}$) waha się od 0,001 (prawdopodobnie dla fragmentów krajobrazu o małym nachyleniu, a więc o mniejszej erozyjności) do 0,07–0,1 $\text{kg TP} \cdot \text{ha}^{-1}$ w ciągu miesiąca, dla obszarów silnie użytkowanych rolniczo (hodowla, pastwiska, osady wiejskie) i/lub o większej erozyjności ze względu na nachylenie. Stężenia TP w okresie letnim dla tego typu cieków wynoszą najczęściej poniżej $0,1 \text{ mg} \cdot \text{l}^{-1}$, rzadziej dochodzą do $0,2 \text{ mg} \cdot \text{l}^{-1}$, natomiast w ciekach z terenów silnie użytkowanych rolniczo mogą dochodzić do $0,5 \text{ mg} \cdot \text{l}^{-1}$. Wartości w zakresie $0,2\text{--}0,5 \text{ mg} \cdot \text{l}^{-1}$ należy uznać za silnie eutrofizujące (tab. 5).

Nie stwierdzono zależności pomiędzy stężeniem i ładunkiem fosforu odprowadzanego w okresie letnim ze zlewni przyjeziornych, a takimi cechami zlewni, jak udział gruntów ornych, gęstość sieci rzecznej, czy średnie nachylenie. Stwierdzono natomiast słabą korelację ujemną pomiędzy przepływem a stężeniem fosforu ogólnego i fosforu rozpuszczonego, wyrażoną w postaci regresji log-log (tab. 6). Wynika z niej, że w miarę rozwoju cieków i wzrostu ich przepływu (w zakresie wartości od 0,001 do $0,25 \text{ m}^3 \cdot \text{s}^{-1}$) stężenie fosforu zarówno ogólnego jak i rozpuszczonego maleje. Podobną zależność stwierdzono również dla cieków Jorki na Pojezierzu Mazurskim. Można postawić wniosek, że w niewielkich ciekach o ogólnie małym przepływie w miarę ich rozwoju i zwiększenia przepływu następuje prawdopodobnie sorpcja fosforu na wleczonych cząsteczkach zawiesiny, a następnie ich sedymentacja w korycie cieku na osadach dennych lub też pochłanianie przez roślinność brzegową. Sytuacja ta może jednak mieć miejsce tylko w warunkach względnie ustabilizowanego i umiarkowanego przepływu.

Wykazano, że wody powierzchniowe jezior wraz z wodami rzek i cieków zasilających je wykazują spójne dla danej zlewni odrębności składu chemicznego w zakresie analizowanych składników, tj. Ca, Mg, N, Na, K, Fe ogólnego oraz w zakresie przewodnictwa elektrolitycznego (rys. 5). W tym zakresie wyróżniają się wody zlewni Szelmentki, gdzie zarówno jeziora jak i cieki wykazują najwyższe lub wysokie wartości, zaś wody jezior i cieków zlewni rz. Czarna Hańcza wykazują najniższe lub jedne z niższych wartości tych składników.

Dla wielu z analizowanych 25 jezior, w tym dla większości jezior mezotroficznym, obserwuje się wyraźnie niższe stężenia Ca, K, Mg i Fe ogólnego jak też przewodnictwa elektrolitycznego w wodach jeziornych (powierzchniowych) w stosunku do wód ich rzecznoego zasilania. Sugeruje to zarówno rozcieńczenie (wyobrażalne w jeziorach głębokich) jak i sedymentację tych związków (szczególnie Ca i Fe ogólnego). Wydaje się, że to ostatnie zjawisko może być przyczyną tendencji do wyższego udziału procentowego P i N w sestonie, mniejszego udziału formy rozpuszczonej i większego stosunku TN : TP w wodach powierzchniowych jezior w porównaniu z wodami ich rzecznoego zasilania (rys. 6).

Wyobrażalny mechanizm byłby następujący: w powierzchniowych wodach jezior zasilanych głównie przez wody cieków następuje wychwytywanie fosforu rozpuszczonego niesionego z ciekami i jego przechodzenie w formę sestonu (stąd wzbogacanie sestonu w ten pierwiastek) zarówno w drodze biologicznego przyswajania jak i sorbowania na materii mineralnej dostającej się do jeziora (związki Ca i Fe). Cząstki te podlegają szybkiej sedymentacji, co powoduje transport fosforu do wód głębszych, a objawem tego jest wzrost relatywnego deficytu P w wodach powierzchniowych jezior w stosunku do wód rzecznych (wzrost stosunku N : P) oraz spadek stężenia związków mineralnych (Ca, Fe) zaangażowanych w procesy sorpcji fosforu.

6. REFERENCES

1. Bajkiewicz-Grabowska E. 1993 – Assessment of watershed impact and sensitivity of lakes to degradation in Suwałki Landscape Park (north-eastern Poland) – *Ekol. pol.* 41: 43–52.

2. Hillbricht-Ilkowska A., Goszczyńska W., Planter M. 1981 – Non point sources of nutrients to the lake watershed of river Jorka, Masurian Lakeland, Poland (In: Impact of non-point sources on water quality in watersheds lakes, Eds. J. A. M. Steenvoorden, W. Rast) – Proc. int. Symp. MAB/5, Amsterdam, 152–183.
3. Hillbricht-Ilkowska A. 1986 – The phosphorus and its bioavailability in the runoff waters exported by the lake watersheds of different geochemical character (In: Land use impact on aquatic ecosystems, Eds. L. Lauga, H. Decamps, M. M. Holland) – MAB/UNESCO Proc. Toulouse Workshop, 49–59.
4. Hillbricht-Ilkowska A. 1988 – Transport and transformation of phosphorus compounds in watersheds of Baltic lakes (In: Phosphorus cycles in terrestrial and aquatic ecosystems, Ed. H. Tiessen) – SCOPE/UNEP Regional Workshop 1 Europe, 193–206.
5. Hillbricht-Ilkowska A. (Ed.) 1989 – Jeziora Mazurskiego Parku Krajobrazowego – stan eutrofizacji, kierunki ochrony [Lakes of Masurian Landscape Park – eutrophication, protection trends] – Ossolineum, Warszawa-Wrocław, 167 pp.
6. Hillbricht-Ilkowska A. 1990 – Factors responsible for retarding the eutrophication rate of some mesotrophic lowland lakes in NE Poland – Int. Rev. gesamt. Hydrobiol., 75.
7. Hillbricht-Ilkowska A., Wiśniewski R. 1993 – Trophic differentiation of lakes of the Suwałki Landscape Park (north-eastern Poland) and its buffer zone – present state changes over years position in trophic classification of lakes – Ekol. pol. 41: 195–219.
8. Hryniewicz R., Przybylska G. 1993 – Actual and predicted air pollution and deposition rates of pollutants in north-eastern Poland – Ekol. pol. 41: 75–106.
9. Kufel L. 1990 – Watershed nutrient loading to lakes in Krutynia (Masurian Lakeland, Poland) system – Ekol. pol., 38, 323–336.
10. Smolska E. 1993 – The dynamics of contemporary morphogenetic processes in the Szeszupa river catchment area (Suwałki Landscape Park, north-eastern Poland) – Ekol. pol. 41: 27–42.