POLISH JOURNAL OF ECOLOGY (Pol. J. Ecol.)	50	4	439–458	2002

Regular research paper

Joanna RYBAK

Department of Hydrobiology, Institute of Ecology PAS, Dziekanów Leśny,
05-092 Łomianki, Poland, e-mail: hasia@post.pl

SEASONAL AND LONG-TERM EXPORT RATES OF NUTRIENTS WITH SURFACE RUNOFF IN THE RIVER JORKA CATCHMENT BASIN (MASURIAN LAKELAND, POLAND)

ABSTRACT: In the Masurian Lakeland a medium size catchment basin of the Jorka river-lake system (about 65 km^2) was studied intensively in 1996–1998 (April– October) and compared with the data from the late 1970s. Nutrients (TP, TKN, N-NO$_3$) and chlorides were monitored in 15 short lakeshore streams draining small subcatchments that differed in land use. The annual and monthly concentration values of nutrients were measured as well as the annual load in kg ha^{-1} year^{-1}.

The data indicate that in a mosaic, hilly region the export rates from the diversified small catchments of both TP and TN tend to be low, lower than in other, non-mosaic areas; the values of export rates are mainly dependent on the discharge in the subcatchments; that is why the values for 1998 and/or 1997 were usually lower than for other years.

There is a tendency to lower concentration for nutrients (including chlorides) and export rates in the subcatchments objected to low impact of agriculture (forest, wetland) than in the subcatchments dominated by cropland. Extremely high values were found for a few catchments with cropland, additionally polluted by sewage disposal in the vicinity.

KEY WORDS: eutrophication, nitrogen, phosphorus, land use, long-term study

1. INTRODUCTION

Runoff of nutrients from the catchment determines significantly the rate of lake eutrophication. Runoff from catchments depends on many factors such as relief and land use, distribution and size of crop fields, meadows, forests, and wetlands. Nitrogen and phosphorus export from agricultural areas, intensively grazed areas, and built-up areas is generally higher than from forests and meadows, and especially from wetlands that function as barriers and filters (Rekolainen 1989, Burt *et al.* 1993, Hillbricht-Ilkowska 1995, Tiessen 1995, Hakala 1998, Rzepecki 2000) and can retain nutrients (Kufel 1991, Vought *et al.* 1994, Hillbricht-Ilkowska *et al.* 1995, Raisin 1996, Uusi-Kamppa *et al.* 1997). To control the rate of nitrogen and phosphorus transport, not only the protection and restoration of wetlands is needed (Mitsch 1992, Weller and Wang 1996, Haycock *et al.* 1997), but also the appropriate distribution of crop fields, their size and proximity to cultivated land, and distance from open waters. For this reasons, a mosaic landscape provides opportunity to control the rate of nutrient export from farmland, in which crop fields are interspersed with the areas of no agricultural use. Diversified relief, structure of land use, and plant cover, also fairly stable agricultural use should minimize the nitrogen and phosphorus export to lakes.

The nitrogen and phosphorus runoff from the catchment is regulated by both hydrological processes and land management (Zalewski *et al.* 1997). Nutrient transport largely depends on the landscape structure, including the structure and management of the catchment, and number and distribution of crop fields (Rekolainen 1989, Burt *et al.* 1993, Hillbricht-Ilkowska *et al.* 2000). Changes in land management, increase in the cover of farmland and decrease in the number of wetlands give rise to increased nutrient runoff (Mander *et al.* 2000). Nitrogen and phosphorus export from mosaic, diversified land with moderate agriculture should be lower as compared with that from less diversified landscape in terms of its relief and use (Hillbricht-Ilkowska 1989).

These issues can be analysed in a long-term study on nitrogen and phosphorus export and its variation in time and space in a catchment with mosaic landscape under forest-agricultural use, such as the lakeland landscape of north-eastern Poland (the Baltic Lakeland Belt), carved during the last glaciations (about 15 000 years ago).

Detailed questions analysed in this paper concern:

- Relationships between the discharge and nutrient concentration.
- Long-term trends in nutrient export from the study area.
- The role of land use in controlling nutrient runoff and loading to lakes.

2. STUDY AREA

The study areas were located in the catchment of the Jorka river (53°45'N to 53°53'N, 21°25'E to 21°33'E). It occupies 63 km^2 of the Masurian Lakeland, north-eastern Poland. The river flows through 5 lakes and is supplied by a dozen streams. The catchment represents a typical postglacial landscape with heterogeneous landforms, land use and cover (Bajkiewicz-Grabowska 1985) (Fig. 1). The land use (arable land contributes to 30–50% of the area) and land cover are highly mosaic. Mozgawa (1995) estimated that the mean size of wetland and meadow patches in a comparable landscape fragment was 0.64–1.89 ha, that of forest patches 1.95–4.50 ha, and cropland size varied from 1.87 to 3.89 ha. High fragmentation of landscape patches is a consequence of the diversified relief of this area (Hillbricht-Ilkowska 1999), for example, the mean number of patches per km^2 in the catchments was 1–12 for meadows and pastures, 3–15 for crop fields, and 2–7 for forest (Rybak 2002). The spatial pattern of cultivated fields is relatively stable and fertilization is moderate (60 NPK ha^{-1}). Forest fragments and wetlands (swamps, peatbogs, mid-field pools) occur as distinct patches, as well as continuous zones of bog vegetation along lake shores and river banks. These zones function as barriers decreasing the load of nutrients transported with surface and groundwater runoff to the lakes (Rzepecki 2002). Moraine relief is dotted with many depressions without outflow (Hillbricht-Ilkowska 1999). The mean size of depressions overgrown with reeds, sedges, alders, willows, and birches (Hillbricht-Ilkowska *et al.* 2000) varies from 0.2 to 4 ha. The relief is also diversified. It consists of numerous ridges and hills, steep slopes, river channels and stream valleys (Bajkiewicz-Grabowska 1985, Hillbricht-Ilkowska *et al.* 2000). The use of the catchment shows a long-term stability; the basic configuration of crop fields remained unchanged for 20 years (Bajkiewicz-Grabowska 1985, Traczyk and Kloss 1985, Rybak 2002). Preserved is spatial division of the whole catchment into the upper part with a low agricultural impact, middle part with a moderate agricultural impact, and lower part with a high agricultural impact (Fig. 1). In the surroundings of Lake Majcz (Fig. 1), where agricultural use is the least developed (Rybak 2002), patches functioning as moderate barriers, such as forests and pastures, are most numerous. Their alternate distribution – meadows and pasture patches being interspersed with forest patches of various sizes, may promote the minimalization of nutrient export. In the surroundings of Lake Jorzec (Fig. 1), with the best-developed agricultural use (Rybak 2002), the proportion of efficient barrier habitats (wetlands), is the highest of all the

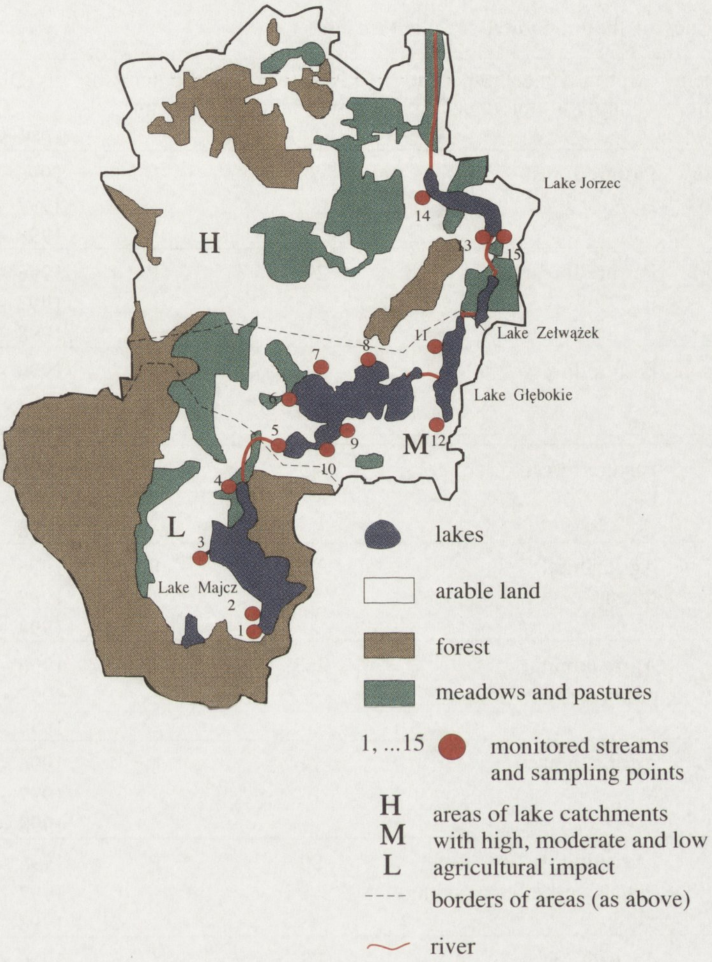


Fig. 1. Outline of the Jorka river catchment: land cover and the monitored streams.

other lake catchments. Crop fields and built-up land occupy large areas (Rybak 2002), and often they are not interspersed with habitats acting as strong barriers such as wetlands and depressions without outflow, or moderate barriers such as forests and pastures. Consequently, the transport of nutrients from the catchment may be high.

3. METHODS

Seasonal and annual variation in the concentration of total phosphorus (TP), Kjeldahl nitrogen (TKN) (the sum of N-NH_4 and N-org.), and nitrates (N-NO_3) flowing with surface waters to the lakes of the Jorka river basin were examined in 1996–1998. In addition, the concentration of chlorides and changes in electrolytic conductivity of water were analysed. Samples were taken at monthly intervals from April through October from 15 streams supplying lakes of the Jorka catchment, at their outlets to lakes (Fig. 1). Subsamples were taken close to the lake shore line across the stream width, and they were combined to obtain a representative sample.

To determine the concentration of chemicals in water samples the following techniques were used, according to the Standard Methods (Golterman *et al.* 1978): the molybdate method for total phosphorus, Sőlorzano method for Kjeldahl nitrogen, Griess method for nitrate nitrogen, and Mohr method for chlorides. The electrolytic conductivity was measured by the WTW conductivity meter.

The velocity of water in streams was measured with a hydrometric flow-meter Hega 1 (a 10% error was involved in these measurements, Bajkiewicz-Grabowska *et al.* 1993). It was recorded once a month

Table 1. Characteristics of the monitored streams (see Fig. 1)

Stream subcatchment – No. of sampling point (see Fig. 1)	Subcatchment type and agricultural impact*	Area of sub-catchment (ha)	Periodicity of stream**	Discharge range Q (m^3 s^{-1}) in April–October 1996–1998
Majcz – 1	Pasture/forest L	99	P	1996 – 0.0003 – 0.202 1997 – 0.0003 – 0.014 1998 – 0.0003 – 0.015
Majcz – 2	Pasture/forest L	292	P	1996 – 0.0003 – 0.085 1997 – 0.0003 – 0.036 1998 – 0.0003 – 0.018
Majcz – 3	Pasture/forest L	30	I	1996 – 0.0003 – 0.004 1997 – ≤0.0003 1998 0.0003
Majcz – 4	Pasture/forest L	45	P	1996 – 0.0003 – 0.014 1997 – ≤0.0003 1998 – 0.0003 – 0.005
Inulec – 5	Agricultural/ forest M	298	P	1996 – 0.0003 – 0.530 1997 – 0.0003 – 0.004 1998 – ≤0.0003
Inulec – 6	Agricultural/ pasture M	263	I	1996 – 0.0003 – 0.004 1997 – ≤0.0003 1998 – 0.0003 – 0.0082
Inulec – 7	Agricultural M	14	P	1996 – 0.0003 – 0.004 1997 – ≤0.0003 1998 – 0.0003 – 0.010
Inulec – 8	Agricultural (intensive cattle breeding) M	80	P	1996 – 0.0003 – 0.006 1997 – ≤0.0003 1998 – 0.0003
Inulec – 9	Agricultural M	78	I	1996 – 0.0003 – 0.006 1997 ≤0.0003 1998 – 0.0003 – 0.0054
Inulec 10	Agricultural M	42	I	1996 0.0003 – 0.002 1997 – ≤0.0003 1998 – 0.0003 – 0.006
Głębokie – 11	Agricultural M	32	P	1996 – 0.0003 – 0.016 1997 – 0.0003 – 0.0005 1998 – 0.0003 – 0.003
Głębokie – 12	Agricultural/ pasture M	104	P	1996 – 0.0003 – 0.008 1997 – 0.0003 – 0.009 1998 – 0.0003 – 0.015
Jorzec – 13	Agricultural (communal sewage disposal in the vicinity) H	35	P	1996 – 0.0003 – 0.256 1997 – 0.0003 – 0.084 1998 – 0.0003 – 0.126
Jorzec – 14	Agricultural (communal sewage disposal in the vicinity) H	1176	P	1996 – 0.0003 – 0.457 1997 – 0.0012 – 0.088 1998 – 0.0003 – 0.100
Jorzec – 15	Agricultural/ pasture H	26	P	1996 – ≤0.0003 1997 – ≤0.0003 1998 – ≤0.0003

*L, M, H – lake subcatchments with low, moderate and high agricultural impact (see Fig. 1),
**P – permanent, I – intermitted.

when water samples were taken. Sensitivity limit of the flow-meter was 0.0003 m^3 s^{-1}.

The streams drain basins of different sizes (from 14 to 1176 ha) (Table 1). In most cases, these are small catchments below 100 ha. The streams under study comprised drainage ditches in farmland, drainage pipes (streams no. 7 and no. 11), and natural streams (no. 14). Some of them could dry out in summer (intermittent streams).

The catchment under study was subdivided into three groups of subcatchments according to their use and cover areas: with a low agricultural impact (catchments of streams no 1–4, draining areas predominantly covered with forests and meadows); areas subjected to moderate agricultural impact (streams no. 5–12, draining cropland); areas with high agricultural impact (streams no. 13–15, draining areas under intensive agriculture and heavy anthropopressure (sewage disposal in the vicinity) (Fig. 1) (Rybak 2002).

It was assumed that nitrogen and phosphorus concentration characterized the mean values for successive months (April–October). For each month, the export of nutrients was calculated as a product of their concentration and water discharge from 1 ha of the catchment. The sum of loads over the period April–October was considered to approximate the annual load.

Load values of phosphorus and nitrogen calculated for 1996–1998, were compared with those calculated by Hillbricht-Ilkowska and Ławacz (1983) and Ławacz *et al.* (1985) for the same subcatchments in 1978; also the data on chlorides for 1978 were compared with those for 1996–1998.

4. RESULTS

4.1. DISCHARGE IN RELATION TO PRECIPITATION

The majority of monitored streams were active all year round. Only four of them – nos. 3, 6, 9 and 10 usually dried up in summer (Table 1). Occasionally more streams are also dried up for several weeks. In the study period, discharge from monitored streams ranged from less than 0.0003 m^3 s^{-1} to 0.580 m^3 s^{-1} (Table 1). On the average, the highest monthly discharge was noted in April, but it largely differed from year to year (Fig. 2). Mean annual discharge was the highest in 1996 (0.0710^6 m^3) and the lowest in 1997 (0.00910^6 m^3) (however year-to-year differ-

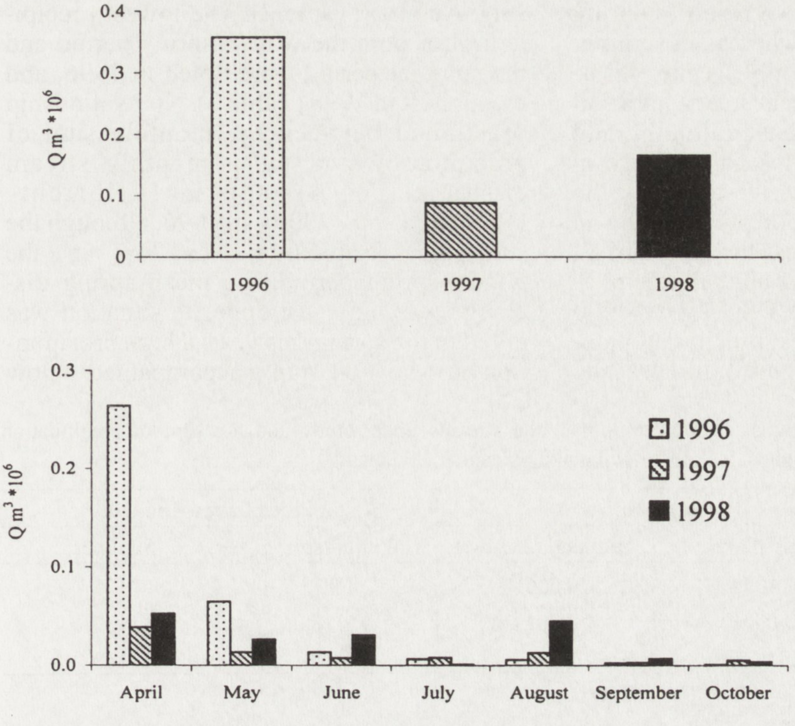


Fig. 2. Mean annual and monthly discharge (n=15) in the monitored streams (Fig. 1, Table 1).

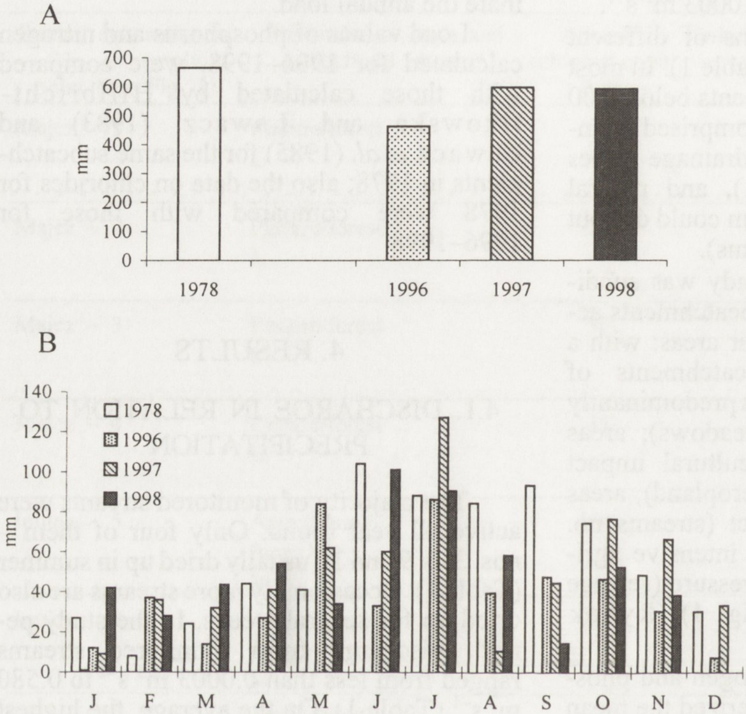


Fig. 3. Annual (A) and monthly (B) sums of precipitation in 1996–1998 for the Jorka river catchment (data of Meteorological Station, Mikołajki, Masurian Lakeland).

ences were not statistically significant, p>0.05) (Fig. 2). In contrast, the sum of precipitation in the period from April to October was the lowest in 1996, while higher and similar in 1997 and 1998 (Fig. 3). The mean stream discharge was higher in spring than in summer (Fig. 2). This was a result of spring flood and snow melting, whereas in summer (July) even heavy rains only weakly influenced stream discharge because of a high soil permeability. A short intense rainfall could give rise to a short-lasting local increase in discharge however ineffective to renew the streams. The annual sum of precipitation in 1996 was 463 mm and it was the lowest of all the years (Fig. 3). A higher annual precipitation was noted in 1997 and 1998 – nearly 600 mm (Fig. 3), but the highest precipitation occurred in July (to 100–200 mm). In 1998, the annual sum of precipitation was 593 mm. Over the study period, the winter–spring sum of precipitation varied from 90 to 168 mm (cumulated data for the period January–April) and in summer from 125 to 148 mm (cumulated data for the period July–August) (Table 2). The lowest precipitation for both the winter–spring period and the summer period were noted in 1996, and the highest in 1998 (Table 2). No relationship was found between the monthly sum of precipitation and mean monthly stream discharge (Fig. 4) (also in Hillbricht-Ilkowska *et al.* 2000). In 1996, although the sum of precipitation was low in the winter–spring period, the mean spring discharge was high. An opposite situation was noted in the spring this year; a high precipitation in May (84 mm), accompanied a low

Table 2. Mean (n=15) monthly discharge (m^3 s^{-1}) in the streams under study and the sum of precipitation (mm) (provided by Meteorological Station in Mikołajki, Masurian Lakeland)

Year	Discharge (m^3 s^{-1})		Precipitation (mm)	
	Spring (April)	Summer (August)	Winter–spring[1]	Summer[2]
1996	0.1054	0.0061	90	125
1997	0.0091	0.0013	118	137
1998	0.020	0.017	168	148

[1] January–April. [2] July–August.

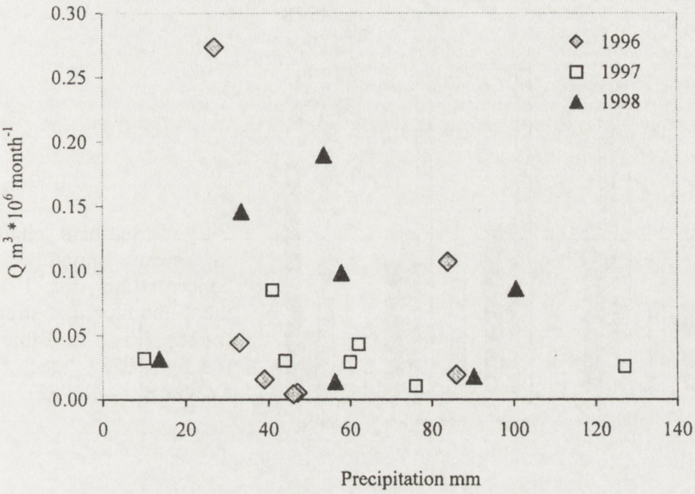


Fig. 4. Relationship between monthly sums of precipitation and mean monthly discharge (from April to October) in the monitored streams (Fig. 1, Table 1).

mean discharge. A similar situation was noted in 1997 and 1998. The highest precipitation in 1997 was noted in July (127 mm), whereas the mean discharge of all the streams was at the limit of measurement sensitivity (0.00110^6 m^3 month^{-1}). In June of 1998, the mean discharge was only 0.00710^6 m^3 month^{-1} at a monthly sum of precipitation of 100 mm, whereas the highest discharge was noted in April at precipitation of 56 mm. In some cases, the relationship between the sum of precipitation and mean discharge was opposite.

4.2. CONCENTRATION AND EXPORT OF TOTAL PHOSPHORUS (TP)

There was a great variation in the TP concentration among different streams, seasons and years. The range of variation covered 5 orders of magnitude from 0.0001 to 1.1 mg l^{-1}. The average of annual TP concentration for all monitored streams was lowest in 1978 (0.05 mg l^{-1}) and highest in 1996 (~0.20 mg l^{-1}). Although the stream-to-stream variation in those years was very high, no statistical difference was found neither among streams nor among years (Fig. 5).

During the period of 1996–1998 the highest annual mean TP concentration (for the group of 15 streams) was noted in 1996 (0.21 mg l^{-1}) and the lowest in 1998 (0.13 mg l^{-1}) (Fig. 5).

In 1996, the mean TP concentration for all the streams varied from 0.07 mg l^{-1} (in October) to 0.36 mg l^{-1} (in April); in 1997 from 0.05 mg l^{-1} (in October) to 0.218 mg l^{-1} (in July), and in 1998 from 0.064 to 0.199 mg l^{-1} (in April and May, respectively) (Fig. 6).

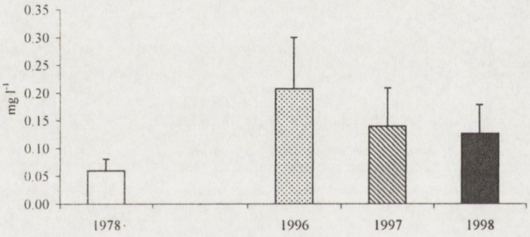


Fig. 5. Mean annual TP concentration (mg l^{-1}) in the monitored streams (n=15) (Fig. 1, Table 1) (data 1978 acc. to Ławacz *et al.* 1985).

In the spring period (April–June), the highest TP concentration was recorded in 1996 (in April 0.36 mg l^{-1}), and the lowest in April 1978 (0.048 mg l^{-1}) (Fig. 6). A similar situation occurred in the summer period – in 1996 highest value was in August (0.25 mg l^{-1}). However differences between seasons were not statistically significant ($p>0.05$). Although a high TP concentration in April were combined with high discharges (Fig. 2), in the remaining months, high TP concentration accompanied low discharges (in August and September).

In 1996, 1997, and 1998, the highest TP concentration were noted in stream no 7 (see Fig. 1, Table 1) draining crop fields (where maximal concentration was 0.95 mg l^{-1}), in stream no. 13 receiving communal sewage (5.36 mg l^{-1}), and in stream no. 14 receiving flow directly from crop fields (0.53 mg l^{-1}).

Differences were observed in average TP concentration between catchment groups that differed in agricultural use (Figs 1 and 7). The highest TP concentration occurred in the stream no. 7 and streams nos.13 and 14 (Table 1), draining catchments with high agricul-

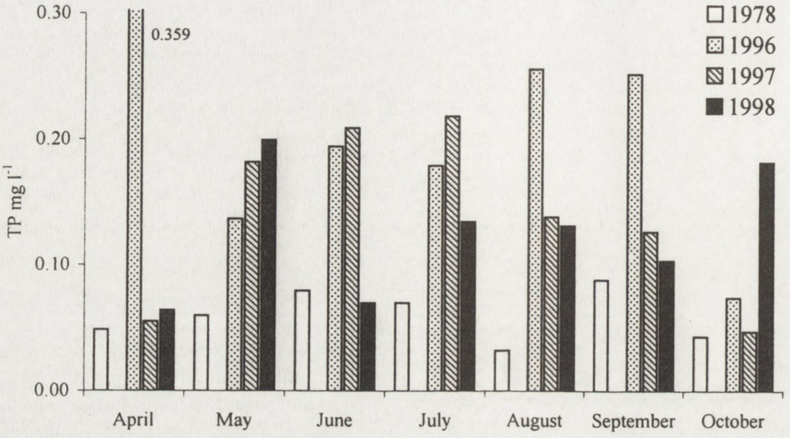


Fig. 6. Seasonal changes in mean monthly TP concentration (mg l^{-1}) in the monitored streams (n=15) (Fig. 1, Table 1) (data 1978 acc. to Ławacz *et al.* 1985).

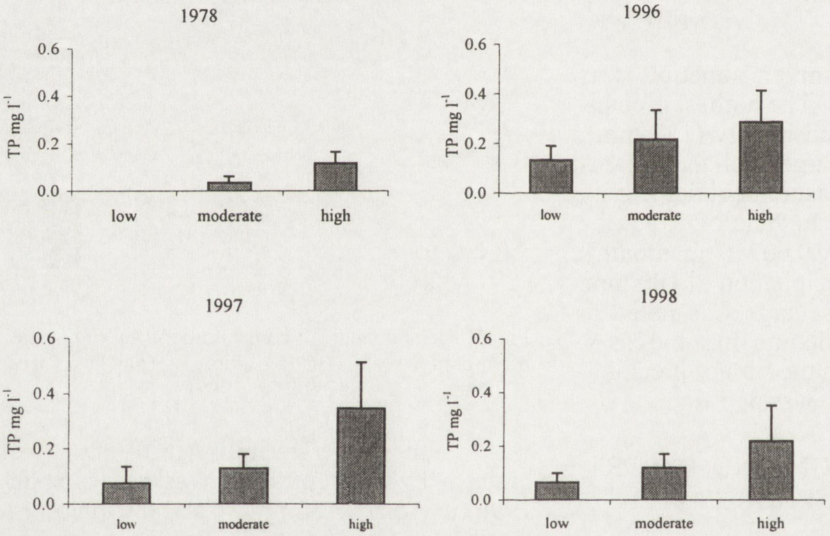


Fig. 7. Mean monthly TP concentration (mg l^{-1}) during April–October in catchment categories that differed in agricultural impact (see Fig. 1, Table 1) (data 1978 acc. to Ławacz *et al.* 1985).

tural impact and with communal sewage. Significant differences ($p<0.05$) were observed between streams draining areas with moderate and high agricultural impact (in 1978, the area under low agricultural impact was not sampled).

TP concentration seem to increase over the 20 year period (Fig. 5) from 0.06 mg l^{-1} on the average in 1978 (Hillbricht-Ilkowska and Ławacz 1983) to 0.14–0.21 mg l^{-1} in 1996–1998, and it was highest in June (0.54 mg l^{-1}) and July (0.31 mg l^{-1}). In all the months, the maximum concentration (significantly higher than in other streams, $p<0.05$) was noted in stream 14 draining catchments under high agricultural impact and heavy anthropopressure. Similarly high concentration in this stream occurred in 1996–1998 (5.36, 1.14 and 3.65 mg l^{-1}, respectively).

The export rate of TP from 1 ha of the catchment to lakes was estimated as a product of concentration and discharge. The sum of TP export rates from April to October was assumed to be close to the annual export. There was a great variation in the annual export rates for different catchments, seasons and years; it ranged from 0.0001 to 10 kg TP ha^{-1} $year^{-1}$. However the most (75%) data ranged:

0.001 to 1 kg TP ha^{-1} $year^{-1}$ in 1978;
0.1 to1.0 kg TP ha^{-1} $year^{-1}$ in 1996;
0.001 to 0.1 kg TP ha^{-1} $year^{-1}$ in 1997;
0.001 to 0.1 kg TP ha^{-1} $year^{-1}$ in 1998.

So, the range of values for 1996 was the narrowest and concentrated around higher values than in other years.

The mean (n=15) annual TP export for successive years was not significantly different; the respective values were as following (kg TP ha^{-1} $year^{-1}$):

0.21 (0.52) in 1978;
0.71 (1.36) in 1996;
0.01(0.29) in 1997;
0.31 (0.94) in 1998.

There is however a tendency to lower export rate in 1997 and 1998 than in 1996.

The highest export rate of TP in the period from April to October was noted in the catchment of stream no 13 receiving communal sewage (Fig. 8) (~5 kg ha^{-1} year^{-1}). Also the highest export rate was observed in streams draining agricultural catchments i.e. streams no. 7 (0.06–0.95 kg TP ha^{-1} year^{-1}), no. 13 (1.14–5.36 kg TP ha^{-1} year^{-1}) and no. 14 (0.12–0.53 kg TP ha^{-1} year^{-1}). In other streams the annual TP export was not higher than 1.13 kg TP ha^{-1} year^{-1}. Generally, TP export was significantly higher ($p<0.05$) in the catchments subjected to high agricultural impact (Fig. 9). The difference between catchments with low and moderate agricultural impact was not significant ($p>0.05$).

The highest export rate occurred in spring (April and May) during the periods of the highest discharge, and in 1996 it was significantly higher ($p<0.05$) than in summer (0.3 kg TP ha^{-1} year^{-1} in April and 0.02 kg TP ha^{-1} year^{-1} in August) (Fig. 10). The highest export rate in these months was a consequence of both high discharge and high phosphorus concentration in these streams.

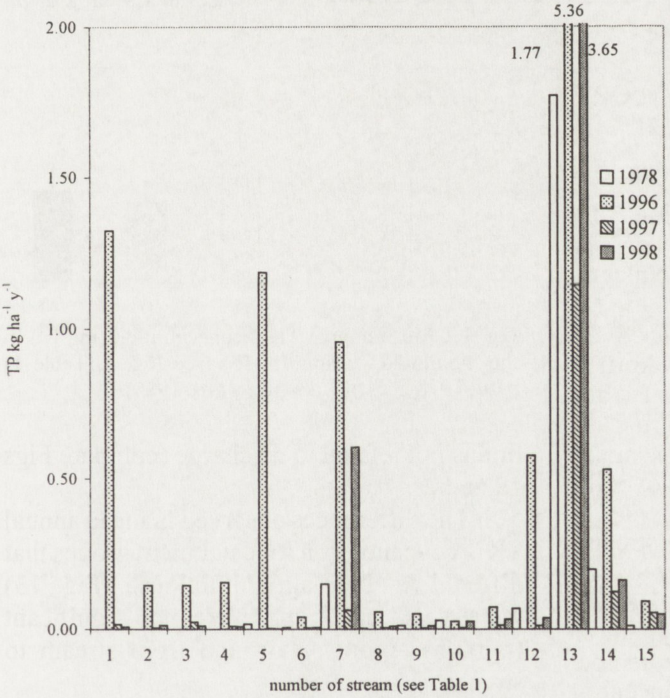


Fig. 8. Annual TP export (during April–October) from individual subcatchments of the monitored streams (Table 1) and four years (data 1978 acc. to Ławacz *et al.* 1985).

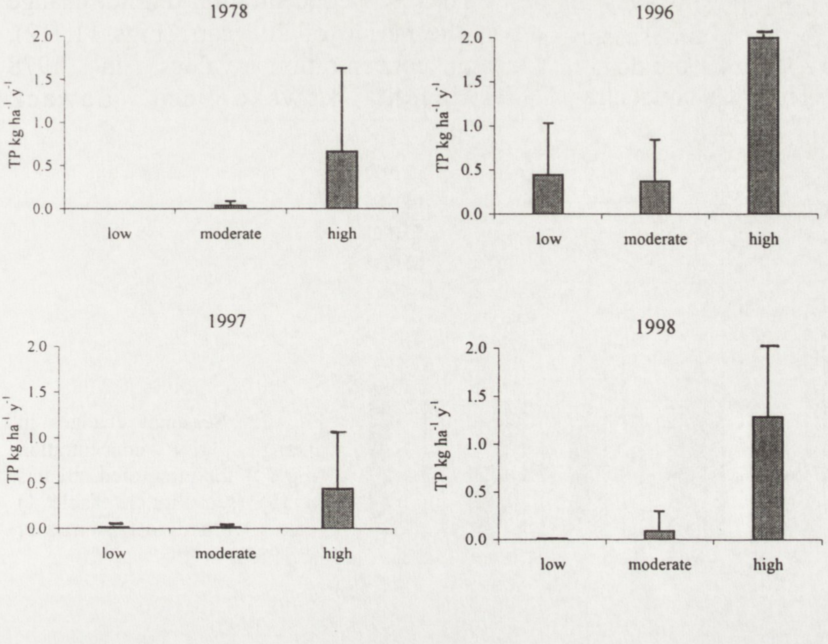


Fig. 9. Mean annual TP export (April–October) from catchment categories that differed in agricultural impact (n=3–8) (see Fig. 1, Table 1) (data 1978 acc. to Ławacz *et al.* 1985).

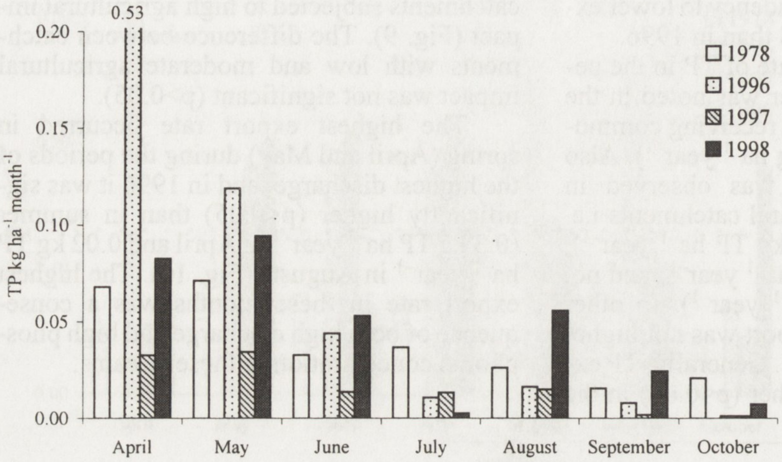


Fig. 10. Seasonal changes in monthly TP export (April–October) from the subcatchments of the monitored streams (n=15) (see Fig. , Table 1) (data 1978 acc. to Ławacz *et al.* 1985).

4.3. CONCENTRATION AND EXPORT RATE OF TOTAL KJELDAHL NITROGEN (TKN)

The TKN concentration values for streams, seasons and years ranged between 0.01–10.0 mg l^{-1}, i.e. four orders of magnitude.

The highest mean (for the group of 15 streams) annual concentration from April to October were noted in 1978 (1.91 mg l^{-1}) and 1996 (1.73 mg l^{-1}), and the lowest in 1997 (1.26 mg l^{-1}), whereas in 1998, the mean TKN concentration in all the streams over the study period was 1.36 mg l^{-1} (Fig. 11). In 1996, mean concentration in all the streams varied from 0.67 mg l^{-1} (in October) to 2.50 mg l^{-1} (in June); in 1997 from 0.65 to 1.72 mg l^{-1} (in October and July, respectively) and in 1998 from 0.71 to 2.0 mg l^{-1} (in September and May). In 1978 very high TKN concentration in July was noted (Fig. 12). Anyway – most of the all data for year and season ranged between 1.0 and 2.0 mg l^{-1} and do not show the high variation. The TKN concentration is not related to discharge (compare Figs 12 and 2).

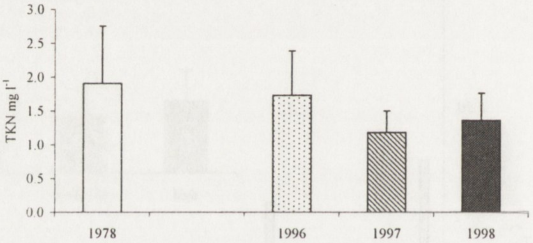


Fig. 11. Mean annual TKN concentration (mg l^{-1}) in the monitored streams (n=15) (see Fig. 1, Table 1) (data 1978 acc. to Ławacz *et al.* 1985).

The differences observed in mean annual TKN concentration for catchment groups that differed in their agricultural use (Fig. 13) were very small and were not significant (p>0.05) among years and from stream to stream.

The TKN concentration did not change over the period of 20 years (Figs 11, 12), mean concentration values in 1978 (Hillbricht-Ilkowska and Ławacz

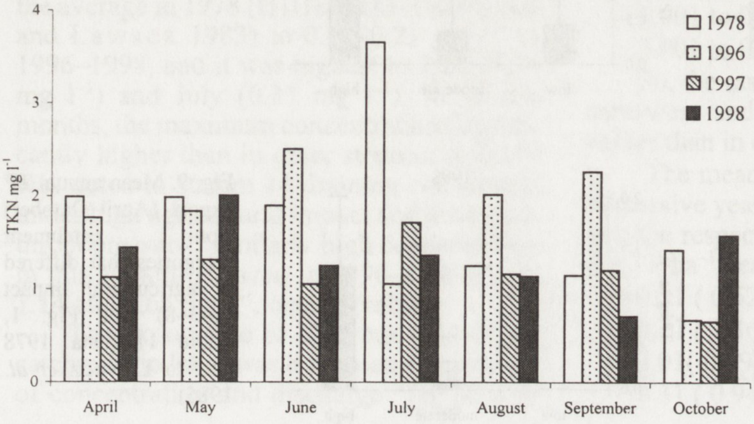


Fig. 12. Seasonal changes in average TKN concentration (mg l^{-1}) for monitored streams (n=15) (see Fig. 1, Table 1) (data 1978 acc. to Ławacz *et al.* 1985).

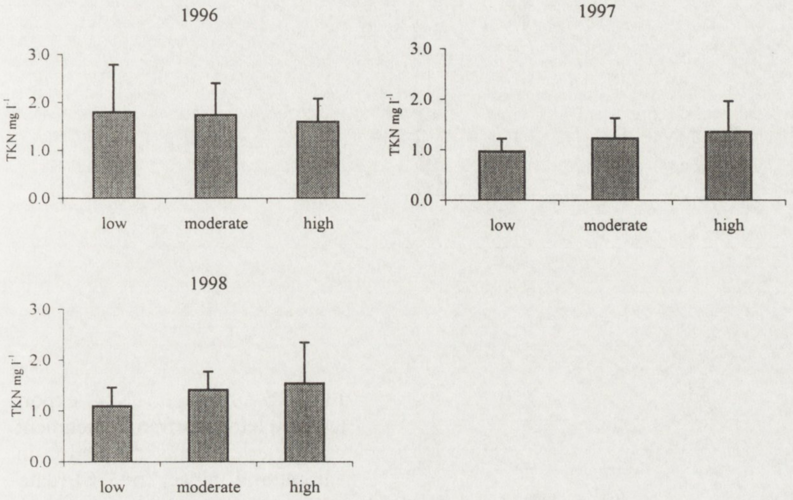


Fig. 13. Mean annual TKN concentration (mg dm^{-1}) during April–October in catchment categories that differed in agricultural impact (n=3–8) (data 1978 acc. to Ławacz *et al.* 1985).

1983) were not significantly ($p>0.05$) higher than in 1996–1998.

The rate of TKN export from 1 ha of the catchment to lakes was estimated as a product of concentration and discharge. The sum of the TKN export during April–October was considered as close to the annual export. The majority of values for respective years varied between:

0.5 – 10.0 kg ha^{-1} $year^{-1}$ in 1978;
0.1 – 10.0 kg ha^{-1} $year^{-1}$ in 1996;
0.05 – 10.0 kg ha^{-1} $year^{-1}$ for both 1997 and 1998.

However most cases were concentrated around 1.0 kg ha^{-1} $year^{-1}$ in 1978 and 1996 and around 0.1 kg ha^{-1} $year^{-1}$ in 1997 and 1998. There was obvious tendency to low rates in last years of study.

The highest mean annual TKN export rate (n=15) was noted in 1996 (6.49 kg $ha^{-1}year^{-1}$), and the lowest in 1997 (1.15 kg $ha^{-1}year^{-1}$), whereas in 1998 it was equal to 3.02 kg $ha^{-1}year^{-1}$. In 1978, the mean annual export rate from the study catchments was 8.72 kg $ha^{-1}year^{-1}$ (Hillbricht-Ilkowska and Ławacz 1983), and it was the highest of all the study years. However year-to-year differences were not statistically significant ($p>0.05$) because of a large variation in export rate over the catchments. Statistically significant differences ($p<0.05$) were noted only between 1978 and 1997, but there was a

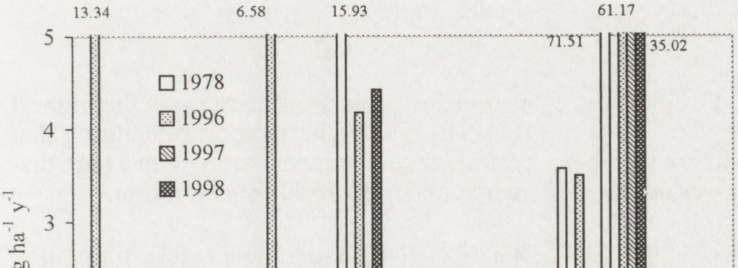


Fig. 14. Annual TKN export (April–October) from individual subcatchments of the monitored streams (data 1978 acc. to Ławacz *et al.* 1985).

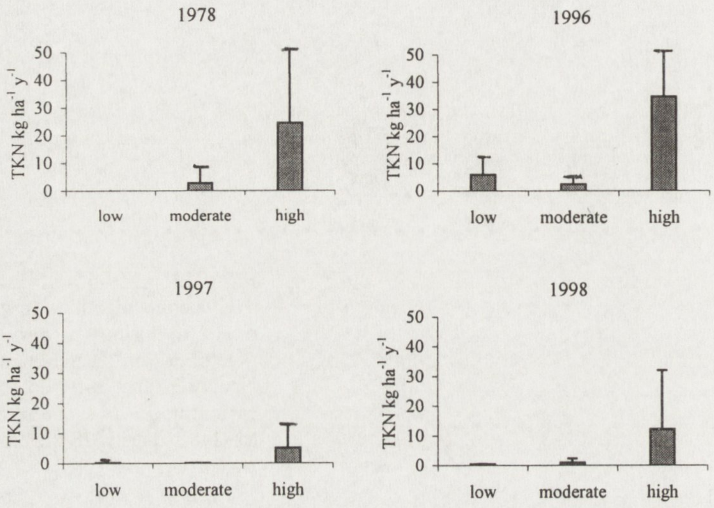


Fig. 15. Annual TKN export (April–October) from catchment categories that differed in agricultural impact (n=3–8) (data 1978 acc. to Ławacz *et al.* 1985).

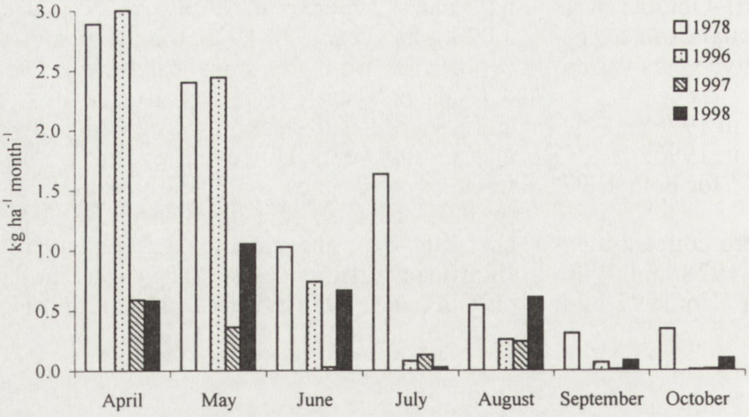


Fig. 16. Seasonal changes in monthly TKN export (April–October) from the subcatchments of the monitored streams (n=15) (data 1978 acc. to Ławacz *et al.* 1985).

declaiming trend to decrease TKN export rates from 1978 to 1998.

The highest export rate of TKN in the period from April through October was noted in all the years in the stream receiving communal sewage, that is, in stream no 13 (Fig. 14). The highest export rates were observed in the streams draining agricultural catchments (streams nos 7, 12, 13, 14, Table 1). They were significantly higher ($p<0.05$) than from the remaining catchments with low or moderate agricultural impact (Fig. 15). The difference between catchments with low and moderate agricultural impact was not statistically significant ($p>0.05$).

The highest export rate was observed in spring (April, May, and June), and in 1978 also in July, when discharge was the highest (Fig. 16). The highest export rate during that period was associated mainly with a high discharge and high TKN concentration.

4.4. CONCENTRATION AND EXPORT RATE OF N-NO$_3$

The range of variation in all values of N-NO$_3$ concentration for streams, seasons and years was wide and varied from 0.001 to 6.01 mg l^{-1}.

Mean annual N-NO$_3$ concentration in all streams was the highest in 1997 and the lowest in 1998 (0.61 *versus* 0.13 mg l^{-1}, respectively) (Fig. 17), and differences between 1996 and 1998, as well as between 1997 and

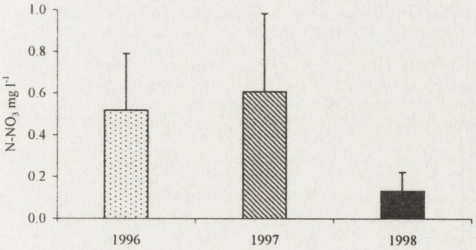


Fig. 17. Mean annual N-NO$_3$ concentration (mg l^{-1}) in the monitored streams (n=15).

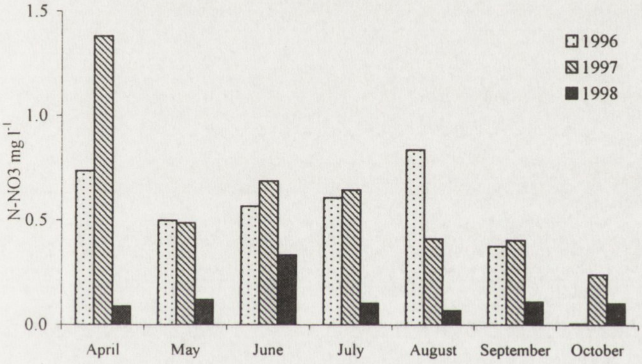


Fig. 18. Seasonal changes in average monthly N-NO$_3$ concentration (mg l^{-1}) in the monitored streams (n=15).

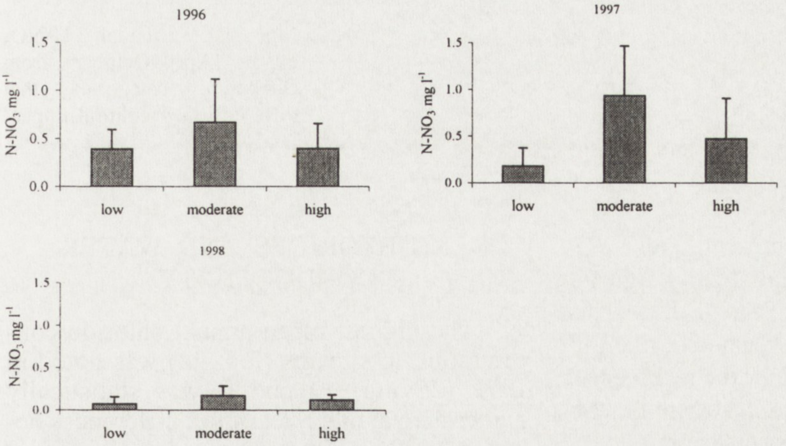


Fig. 19. Mean annual N-NO$_3$ concentration (mg l^{-1}) during April–October in catchment categories that differed in agricultural impact (n=3–8).

1998 were statistically significant ($p<0.05$). A higher mean concentration was observed in the spring and summer 1997 and 1998 than in autumn (Fig. 18) and in both 1996 and 1997 in comparison with 1998. It can be said that in the whole year 1998 the concentration of N-NO$_3$ was extremely low in all streams and seasons (Fig. 18). In 1996 and 1998, no significant differences were found ($p>0.05$) between catchments that differed in agricultural impact (Fig. 19). Only in 1997, differences between catchments with low and moderate agricultural impact were significant ($p<0.05$).

Export rate of N-NO$_3$ from 1 ha of the catchment to lakes was estimated (as the product of concentration and discharge). The sum of N-NO$_3$ monthly export during the April–October period was assumed to be close to the annual value. The annual value of all data varied between 0.001 to 10 kg ha^{-1} year^{-1}, but the range for 1996 and 1997 was narrow and in most of the cases between 0.01 and 0.1 kg ha^{-1} year^{-1}. The range of N-NO$_3$ export rates for 1998 was wide (0.001–1.00 kg ha^{-1} year^{-1}), but most of the cases concentrated around 0.01 kg ha^{-1} year^{-1}. One could say that, like concentration, also the N-NO$_3$ export rate was lower in 1998 than in the previous years.

The highest mean annual export of N-NO$_3$ during the study period was noted in 1996 (1.34 kg ha^{-1} year^{-1}), and a lower in both 1997 (0.14 kg ha^{-1} year^{-1}) and 1998 (0.22 kg ha^{-1} year^{-1}). In 1978, N-NO$_3$ was not analysed. Although large differences were ob-

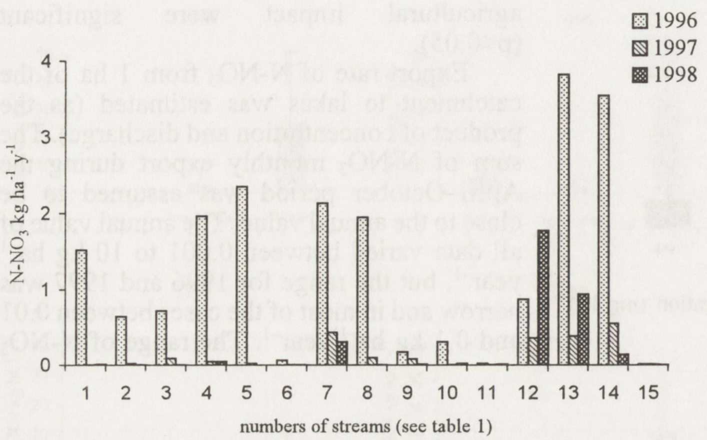


Fig. 20. Annual N-NO$_3$ export (April–October) from individual subcatchments of the monitored streams.

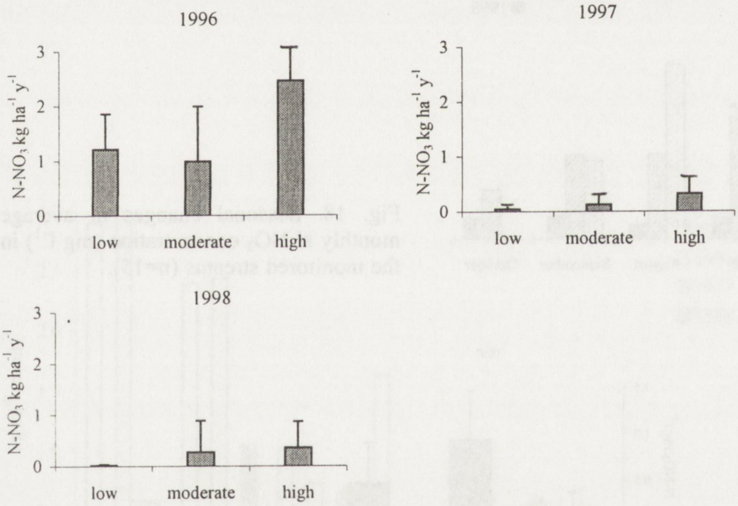


Fig. 21. Annual N-NO$_3$ export (April–October) from catchment categories that differed in agricultural impact (n=3–8).

served between 1996 as compared with 1997 and 1998, they were not statistically significant because of a large scatter of data. The highest annual export rate was noted, like for TP and TKN, in stream no 13 – the receiver of communal sewage, and also in stream no. 14 (Fig. 20). The highest N-NO$_3$ export rate in the period April–October was noted in streams draining catchments with high agricultural impact, but differences between catchment categories were small and statistically not significant (Fig. 21). The highest export rate occurred in spring (April and June) but only in 1996 it was significantly higher in spring ($p<0.05$) than in the other months (Fig. 22). The highest export rate in that period was related with high discharge and high N-NO$_3$ concentration in the streams affected by high agricultural impact.

4.5. CHLORIDES AND WATER CONDUCTIVITY

The highest mean annual chloride concentration in streams (Fig. 22) was noted in 1978 (25 mg l^{-1}) and it was statistically higher than in other years, but differences between 1996–1998 were not significant ($p>0.05$). The higher Cl$^-$ concentration in stream water in 1978 was observed each month (Fig. 24). Chloride concentration was much higher in agricultural catchments compared with forest catchments: 30 mg l^{-1}in catchments with high agricultural impact, about 25 mg l^{-1} with moderate impact, and <10 mg l^{-1} with low agricultural impact (Fig. 25). Differences between catchments that differed in agricultural impact were statistically significant in 1996, 1997 and 1998 ($p<0.05$). No differences were found ($p>0.05$) in chloride concentration between

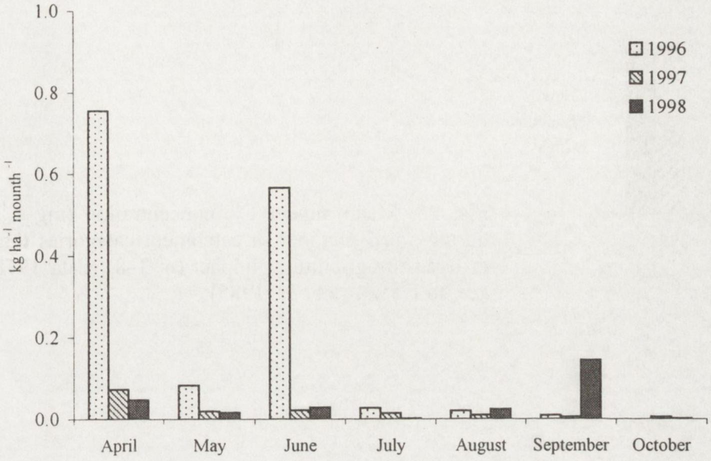


Fig. 22. Seasonal changes in monthly N-NO_3 export (April–October) from the subcatchments of the monitored streams (n=15).

spring and summer in all the catchments and years.

Electrolytic conductivity was measured in 1997 and 1998. In both these years the annual mean values were about 500 µS cm^{-1}. No significant differences were found between these years, nor between categories of streams, except for the spring of 1997, when lower values (400–450 µS cm^{-1}) were found (Fig. 26). The conductivity in streams draining catchments with low and moderate agricultural impact differed significantly ($p<0.05$). Also differences between the spring and summer of 1998 were significant ($p<0.05$) (Fig. 26).

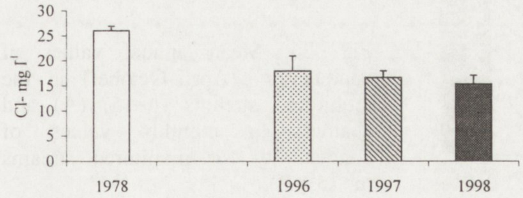
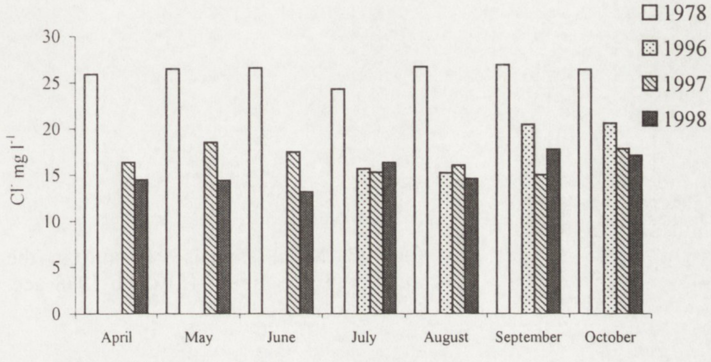


Fig. 23. Mean annual Cl^{-} concentration (mg l^{-1}) in the monitored streams (n=15) (data 1978 acc. to Ławacz *et al.* 1985).

4.6. NITROGEN PHOSPHORUS (N:P) RATIO

Basing on Ławacz *et al.* (1985), the nitrogen to phosphorus ratio was calculated for 1978. The mean value of this index in 1978 (100) was much higher than in 1996–1998. The highest mean N:P ratio in waters of all the streams was noted in 1978 – close to 100. In the years 1996–1998, the respective values were much lower (18–38) (Fig. 27). In most cases, this ratio was the highest in streams draining catchments with low agricultural impact, and it was the lowest in streams draining catchments with high agricultural impact (Fig. 28). In waters of streams crossing the land under high agricultural impact (catchments with a high proportion of crop fields and fertilized meadows, also human settlements), the N:P ratio was the lowest over the study period, and also in 1978. These streams carried high, often the highest of all the streams, loads of phosphorus in both 1996–1998 and 1978. The highest N:P ratio was found in 1978 in streams draining catchments with moderate agricultural impact,



no data for April, May and June 1996.

Fig. 24. Seasonal changes in average Cl^{-} concentration (mg l^{-1}) in the monitored streams (n=15) (data 1978 acc. to Ławacz *et al.* 1985).

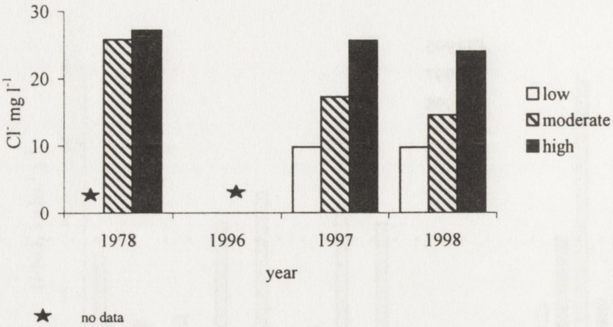


Fig. 25. Mean annual Cl^- concentration (mg l^{-1}) during April–October in catchment categories that differed in agricultural impact (n=3–8) (data 1978 acc. to Ławacz *et al.* 1985).

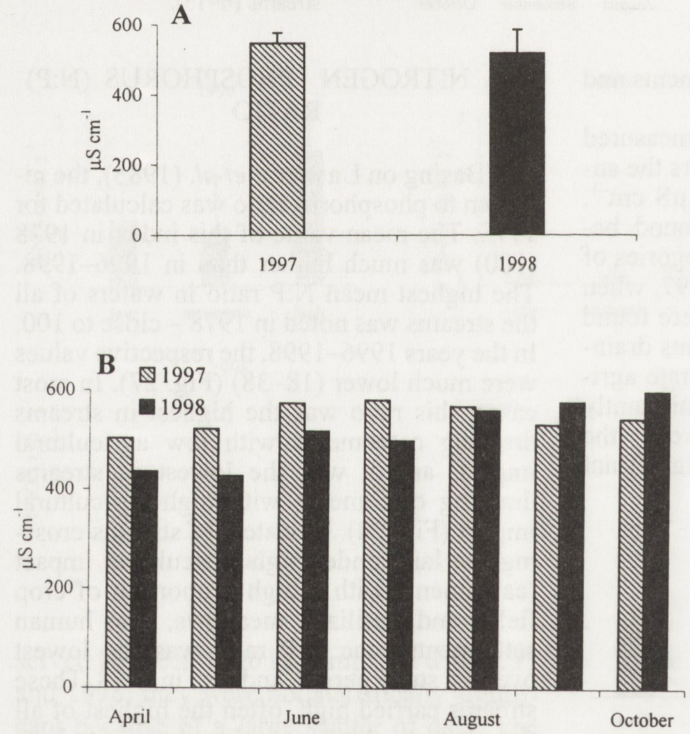


Fig. 26. Mean annual values of conductivity (April–October) in the monitored streams (n=15) (A) and changes in monthly values of conductivity for monitored streams (n=15) (B).

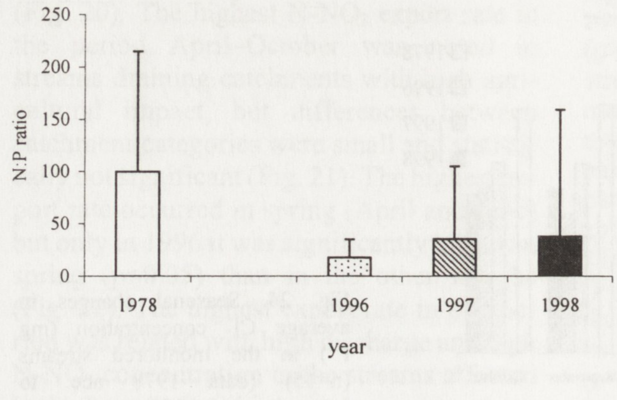


Fig. 27. Mean annual N:P ratio in the monitored streams (n=15) (data 1978 acc. to Ławacz *et al.* 1985.

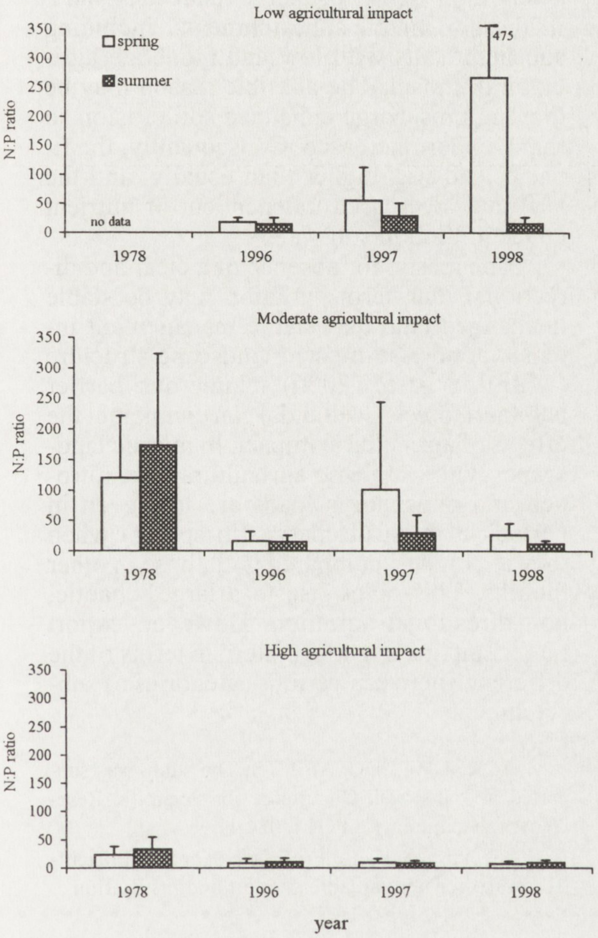


Fig. 28. Mean annual N:P ratio in three subcatchments that differed in the agricultural impact (data 1978 acc. to Ławacz *et al.* 1985).

whereas in 1998 in streams flowing through areas with low agricultural impact. In streams draining areas with low agricultural impact, differences in N:P ratio between years were statistically significant ($p<0.05$). In streams flowing through subcatchments with moderate agricultural impact, N:P ratio significantly decreased since 1978, and in 1996–1998 it was maintained at the similar level. No significant differences ($p>0.05$) were found between years in streams crossing subcatchments with high agricultural impact.

5. DISCUSSION and CONCLUSIONS

A comparison of the rate of annual export of nitrogen and phosphorus from 1 ha of the catchment with literature data shows that it was low in the diverse lakeland landscape subjected to forest/agricultural use.

A large variation was found in the export rates of nitrogen and phosphorus from subcatchments of the river Jorka system in both time and space.

Comparing the annual export of N and P from the Jorka river catchment with that found by various authors with respect to land use in the catchment, it may be concluded that it was low (Kajak 1979, Hillbricht-Ilkowska 1989, Hillbricht-Ilkowska *et al.* 1995): phosphorus export from predominantly agricultural land varied between 0.06 and 0.8 kg ha^{-1} year^{-1}, and from mostly forest land between 0.05 and 1 kg ha^{-1} year^{-1}. According to Rekolainen (1989), phosphorus export varied from 0.11 to 0.16 kg ha^{-1} year^{-1} in catchments under forests and pastures, and from 0.9 to 1.8 kg ha^{-1} year^{-1} in agricultural catchments. Kufel (1991) noted that the phosphorus export from agricultural areas varied between 0.45 and 3.60 kg ha^{-1} year^{-1}, and from a forest catchment between 0.06 and 4.07 kg ha^{-1} year^{-1}. Nitrogen export showed a similar pattern. The highest nitrogen export was noted in streams draining agricultural catchments. Kajak (1979) found that nitrogen export from farmland varied from several to several ten kg ha^{-1} year^{-1}, whereas it was several kg ha^{-1} year^{-1} from meadows and pastures. Also nitrogen export, like that of phosphorus, was generally similar in the Jorka catchment as compared with those found by Rekolainen (1989) and Hakala (1998): 0.9–1.8 kg ha^{-1} year^{-1} of phosphorus and 7.6–20 kg ha^{-1} year^{-1} of nitrogen from agricultural areas, whereas 0.1 kg ha^{-1} year^{-1} of phosphorus and 2.0–2.7 kg ha^{-1} year^{-1} of nitrogen from forest areas.

There were no consistent long-term trends in nutrient concentration and export rates during the study period: in the late 1970s and the late 1990s.

Year-to-year variation was significant (three to five orders of magnitude) as well as variation among the 15 study subcatchments. However, the respective values for 1997 and 1998 i.e. the years with a low average discharge tended to be lower than for years with a high discharge (1996). It is why the monthly highest values of rates are usually found in the spring period i.e. April–May.

During the study period, differences in nutrient export rates were maintained among the three areas under differential agricultural impact.

Differences were found in the concentration and export of TP and TKN between catchments with different agricultural impact (Fig. 1). The largest differences occurred between catchments with low and high agricultural use, and lower between catchments with low and moderate agricultural impact, probably as a result of too small differences in land use between the two categories. Differences were also observed in N-NO_3 export from the catchments with low and high agricultural impact. The export rate of N-NO_3 from the catchment with a high agricultural impact was higher than from the catchment with low and moderate agricultural impact. This was also the case of chloride concentration. Differences in their concentration were lower in streams draining catchments with low agricultural impact than in other streams. According to Kajak (1979), the lowest export rates of nitrogen and phosphorus occurred in forests and meadows, and the highest in areas with intensive agriculture and animal husbandry.

Also the nitrogen to phosphorus ratio was the lowest in streams flowing through agricultural catchments. During the present study period as well as in 1978, this ratio was lower in streams draining farmland than in streams draining catchments with low agricultural impact. Areas subjected to high agricultural impact, permanently and independent of discharge maintained N:P ratio characteristic of eutrophic conditions (10–29). Less transformed areas were more variable from year to year (from 20 to 131), especially in the period of spring thawing, when in 5 cases out of 7, N:P was higher than in summer. In 1996, a very high discharge in spring mobilized N and P, and heavy erosion removed both nutrients in similar proportions, hence this ratio was rather low (18–21). In the areas of intensive agriculture, the N:P ratio ranged 10–29 (being close to Redfield ratio) and could enhance eutrophication, independently of discharge and nutrient loads. Less transformed lands were less variable from year to year, especially in the period of spring thaw, when discharge was the highest. In most cases the N:P ratio was higher in spring (>50) than in summer (<30). In 1996, a very high spring discharge reduced N and P in the soil of all subcatchments, including subcatchments with low and moderate agricultural impact. The possible reason may be that high discharge enhanced soil erosion so that P export increased. Consequently, the final P load was higher than usually, and the N:P ratio decreased independent of nutrient concentration in soil waters.

The reason for absence of a clear and directional long-term variation may be stable unchanged land use, stable management intensity, and also mosaic landscape structure (Mander *et al.* 2000). Numerous barrier habitats (forests, wetlands) can counteract the effects of agricultural impact. In mosaic landscapes with stabilized agricultural use, nitrogen and phosphorus loads are low even in periods of high discharge (in spring) when they are highest compared with those in other months. This gives rise to a large, chaotic, non directional variation. However, export rate maintains a spatial pattern in terms of the difference between various categories of subcatchments.

ACKNOWLEDGEMENTS: The study was supported by the Polish Committee for Scientific Research; project number 6 PO4 F 024 11.

Special thanks to Professor Anna Hillbricht-Ilkowska for her valuable support and inspiration.

6. SUMMARY

In a lakeland region (the Masurian Lakeland), the medium size catchment basin of a river-lake system (the Jorka river system) (about 65 km^2) (Fig.1) was studied intensively in 1996–1998 (April–October). Nutrient (TP, TKN, N-NO_3) and chloride were monitored in 15 small lakeshore streams draining small subcatchments from 14 to 1176 ha (Table 1) of different land use (Table 1, Fig. 1). The annual and monthly concentration values of nutrients were measured as well as the annual load in kg ha^{-1} $year^{-1}$. The respective values were compared with the data from 1978 published by Hillbricht-Ilkowska and Ławacz (1983).

Although generally the discharge was very low in the system (range from 0.0003 to 0.503 m^3 s^{-1}), a strong seasonal variation (maximal during the spring freshet) was found with a tendency to very low values in 1997 and/or 1998 (dry and/or warm years) (Fig. 2, Table 1). There was no direct relation between the precipitation and discharge (Table 1, Figs 3, 4).

Generally, the mean TP concentration in streams was higher in the 1990s than in the 1970s (Figs 5, 6, 7), the highest values (up to 0.5 mg l^{-1}) being found in a few streams draining the cropland and receiving sewage disposal. Also a great variation was found in the values of TP export rates for different streams, years and seasons (Figs 8, 9, 10). However there was a tendency to higher values in 1996 (mean 0.71 kg ha^{-1} $year^{-1}$) than for other years and the value for 1997 was the lowest one. Again the highest values (up to 5.0 kg ha^{-1} $year^{-1}$) were found for the spring periods and in the streams polluted with sewage disposal. The data for these streams make the annual values for the catchment with highest agricultural input usually the highest ones. However, generally the most often values of TP export rates in the study area were of the order 0.01 kg ha^{-1} $year^{-1}$ which is much lower than for other, lowland , non-mosaic regions; rarely they reach 0.1. kg ha^{-1} $year^{-1}$.

The values of the concentration and the export rates of TKN varied in a narrower range than those of TP (Figs 11, 12, 13). Most values were concentrated round 0.1 kg ha^{-1} $year^{-1}$ in 1997/1998 while round 1.0 kg ha^{-1} $year^{-1}$ in the 19970s and in 1996 (Figs 14, 15, 16). The few streams draining the cropland and polluted accounted for the highest values of TKN export rates (up to 30 kg ha^{-1} $year^{-1}$) for the catchments with high agricultural impact.

The lowest values of $N\text{-}NO_3$ concentration and export rates were noted in 1998 (there is no data for 1978) and they were higher than 2.0 kg ha^{-1} $year^{-1}$ while in other situations mostly below 0.5 ha ha^{-1} $year^{-1}$ (Figs 17, 18, 19, 20, 21, 22).

The concentration of chlorides tended to be lower in the 1990s than in the 1970s and it was significantly higher for the streams draining the cropland (Figs 23, 24, 25).

Because of a generally strong and multidirectional variation in TP as compared with TKN and $N\text{-}NO_3$, a more distinct decrease in the TN:TP ratio was found in the late 1990s than in the late 1970s (Figs 27, 28).

The data indicate that:

- In a mosaic, hilly region the export rates of both TP and TN from diversified small catchments tend to be low, lower than from non-mosaic areas.
- The values of export rates are mainly dependent on the discharge in the subcatchments: that is why the values for 1998 and/or 1997 were usually lower than for other years .
- There is a tendency to lower concentration values (including chlorides) and export rates in the subcatchments subjected to low impact of agriculture (forest, wetland) than for the subcatchments dominated by cropland (high impact of agriculture) The extra large values were found for a few catchments under cropland, additionally polluted with sewage disposal in the vicinity.

7. REFERENCES

Bajkiewicz-Grabowska E. 1985 – Geographical description, hydrographic components and man's impact in river Jorka watershed – Ekol. pol. 33: 201–224.

Bajkiewicz-Grabowska E., Magnuszewski A., Mikulski Z. 1993 – Hydrometria [Hydrometry]. – PWN, Warszawa, 313 pp. (in Polish).

Burt T. P., Heathwaite A. I., Trudgill L. T. 1993 – Nitrate (processes, patterns and management) – John Wiley & Sons, Chichester, New York, Brisbane, Toronto, Singapore, 444 pp.

Golterman H. L., Clymo R. S., Ohnstad M. A. M. 1978 – Methods for physical and chemical analysis of fresh waters – Blackwell Scientific Publications, Oxford, London, Edinburgh, Melbourne, 214 pp.

Hakala I., 1998 – Some observations concerning changes in the major nutrient loads to lake Pääjärvi during last 25 years – Lammi Notes 25: 4–7.

Haycock N. E., Burt T. P., Goulding K. V. T., Pinay G. 1997 – Buffer zones: their processes and potential in water protection – Quest International, 322 pp.

Hillbricht-Ilkowska A. 1989 – Transport and transformation of phosphorus compounds in watersheds of Baltic lakes. (In: Phosphorus cycling in terrestrial and aquatic ecosystems, Ed. H. Tiessen) – SCOPE/UNEP, Saskatchewan Inst., 193–206 pp.

Hillbricht-Ilkowska A. 1995 – Managing ecotones for nutrient and water – Ecology International 22: 73–93.

Hillbricht-Ilkowska, A. 1999 – Jezioro a krajobraz: związki ekologiczne, wnioski dla ochrony [Lake *versus* landscape: ecological relationships, implications for protection] (In: Funkcjonowanie i ochrona eosystemów wodnych na obszarach chronionych [Functioning and protection of water ecosystems on protected areas] Eds: Zdanowski, B., Kamiński, M., Martyniak, A.) – Wydawnictwo IRS, Olsztyn, 562 pp. (in Polish).

Hillbricht-Ilkowska A., Ławacz W. 1983 – Land impact, loading and dynamics of nutrients – Ekol. Pol. 31: 539–585.

Hillbricht-Ilkowska A., Rybak J., Rzepecki M. 2000 – Ecohydrological research of lake-watershed relations in diversified landscape (Masurian Lakelands, Poland) – Ecological Engineering 16: 91–98.

Hillbricht-Ilkowska A., Ryszkowski L., Sharpley A. N. 1995 – Phosphorus transfer and landscape structure: riparian site and diversified land use pattern (In: Phosphorus in the global environment (transfers, cycles and management, Ed. H. Tiessen) – SCOPE/UNEP. 54: 201–228.

Kajak Z. 1979 – Eutrofizacja jezior [Eutrophication of lakes] – PWN, Warszawa, 233 pp. (in Polish).

Kufel L. 1991 – Watershed nutrient loading to lakes in Krutynia system (Masurian Lakeland, Poland) – Ekol. pol. 38: 323–336.

Ławacz W., Goszczyńska W., Kurowski C., Tomaszewski K. 1985 – Nutrient input with water transport – Ekol. pol. 33, 2: 271–300.

Mander Ü., Kull A., Kuusements V. 2000 – Nutrient flows and land use change in a rural catchment: a modelling approach – Landscape Ecology, 15: 187–199.

Mitsch W. J. 1992 – Landscape design and the role of created, restored and natural riparian wetlands in controling nonpoint source pollution – Ecological Engineering, 1: 27–29.

Mozgawa J. 1995 – Zastosowanie zdjęć lotniczych do charakterystyki ekotonalności i mozaikowości krajobrazu na przykładzie pojeziernych krajobrazów Polski północno-wschodniej [The use of aerial photographs to characterize ecotones and mosaics in landscapes as exemplified by Lakeland landscapes of noth-eastern Poland] – Zesz. Nauk. Kom. "Człowiek i Środowisko", 12: 15–26 (in Polish).

Raisin G. W. 1996 – The role of small wetlands in catchment management: their effect on diffuse agriculture pollutants – Int. Rev. ges. Hydrobiol. 81: 213–222.

Rekolainen S. 1989 – Phosphorus and nitrogen load from forest and agricultureal areas in Finland – Acta Fennica 19: 95–107.

Rybak J. (in press) – N:P ratio in water input to lakes: long-term variation and effects of land use – Verh. Internat. Verein. Limnol.

Rybak J. 2002 – Landscape structure (patch pattern) of the Jorka river catchment (Masurian Lakeland, Poland): analysis of air photos – Pol. J. Ecol. 50: 427–438.

Rzepecki M. 2000 – Wetlands in lake protection: nutrien dynamics and removal in ecotones of a river-lake system (Masuran Lakeland, Poland) – Verh. Internat. Verein. Limnol., 27: 1685–1689.

Rzepecki M. 2002 – Wetland zones along lake shores as barrier systems: field and experimental research on nutrient retention and dynamics. Pol. J. Ecol. 50: 527–541.

Tiessen H. 1995 – Phosphorus cycling in terrestial and aquatic ecosystems – SCOPE/UNEP. Saskatchewan, 339 pp.

Traczyk T., Kloss M. 1985 – Spatial structre of land management in the Jorka river watershed – Pol. ecol. Stud. 11, 2: 239–246.

Uusi-Kamppa J., Turtola E., Hartikainen H., Ylaranta T. 1997 – The interactions of buffer zones and phosphorus runoff (In: Buffer zones: their processes and potential in water protection. Eds: N.E. Haycock, T.P. Burt, K.U.T. Goulding and G. Pinay) – Quest International, pp. 43–53.

Vought L., Dahl J., Pedersen C. L., Lacoursiere J. O. 1994 – Nutrient retention in riparian ecotones – AMBIO 23: 342–351.

Weller C. M., Wang D. 1996 – Role of wetlands in reducing phosphorus loading to surface water in eight watersheds in the Lake Champlain Basin – Environmental Management, 20: 731–739.

Zalewski M., Janauer G. A., Jolankai G. 1997 – Ecohydrology – a new paradigm for the sustainable use of aquatic resources (conceptual background, working hypotheses, rationale and scientific guidance for the implementation of IHP–V Project 2.3 and 2.4 – UNESCO, Paris, pp. 57.

(*Received after revising January 2002*)