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WATERSHED NUTRIENT LOADING TO LAKES IN KRUTYNIA (MASURIAN LAKELAND, POLAND) SYSTEM*

ABSTRACT: Amounts of various forms of nitrogen and phosphorus as well as suspended solids and chlorides carried by waters of 17 streams were analysed. The seasonal dynamics of nutrient runoff from watershed was measured and the attempts undertaken to relate nutrient loading to the character of watershed drained by stream. In conclusion the effect of nutrient runoff on selected lakes was presented.

KEY WORDS: nutrients, watershed, lake, runoff, agriculture, forest, wetlands.

1. INTRODUCTION

Increasing eutrophication of lakes focuses public attention on the sources of nutrients coming down to lakes. Three of them are considered to be the most important: point sources (domestic sewage and industrial waste waters), land runoff and atmospheric deposition. The proportion of particular sources in total nutrient load may vary. For example, nonpoint sources delivered over 50% of phosphorus to North American Great Lakes and Lake Superior was almost entirely fed from those sources (R a s t 1981). It may, however, vary according to the degree of sewage purification, field fertilization intensity, long distance atmospheric transport and so on.

While it is technologically possible to remove nitrogen and phosphorus to satisfactory degree from point sources, the diffuse sources present a substantial problem in lake eutrrophication. In the absence of industry and large town agglomerations the agricultural land management is the main factor that governs nutrient runoff and eutrophication of lakes.

The process of nutrient outwashing from soils depends on many factors. The

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hydrological regime affects strongly the dynamics of nutrient runoff (K u z n e c o v 1986). The amounts of nutrients vary according to land configuration (W i l k i n and H e b e l 1982), to rates of field fertilization (P r o c h ǎ z k o v ǎ 1980), type of fertilizer applied and technological measures used in the field (W e g e n e r 1980). Nutrients already washed out may be transformed and/or accumulated during the transport along watercourses before they reach the lake (P i l l e b o u e 1987). Anyway, there are numerous papers that give the evidence for the impact of watershed runoff upon the lake nutrient budget (see review by K a j a k 1980). Some doubts arise, however, in determining the unit runoff and losses rates from land, especially in case of heterogenous watersheds, and results may vary according to the method applied (Ł a w a c z et al. 1985, P i l l e b o u e 1987).

This paper aims at presenting the amounts and variability of nutrient loading from watershed to lakes of a lowland Krutynia River system. The attempt is also undertaken to relate nutrient loads to the type of land use within the heterogenous watersheds.

2. MATERIALS AND METHODS

Krutynia is a small lowland river of the total length of 94 km. The postglacial watershed of the river covers an area of 638 km^2 (K o n d r a c k i and M i k u l s k i 1958). There are 93 lakes in the watershed, the river itself flows through 18 of them. Most of the lakes are small basins less than 50 ha and only 15 of them exceed 100 ha of area.

For the purpose of the present paper 16 small partial watersheds were selected, each represented by a stream that drains its waters to the lake. One additional stream for comparison was also selected in the Mikołajskie Lake drainage basin. Location of these watersheds is presented in Figure 1 and their general description given in Table 1. The borders of particular watersheds were drawn by Dr. E. Bajkiewicz-Grabowska (Warsaw University) on the regional maps to the scale 1 : 25 000. The same maps served for the estimation of the parts of selected watersheds occupied by agriculture, forests and wetlands.

Sampling of water was performed three times: in April, June and September. Three water subsamples were taken in time intervals of several minutes from each of the selected streams. At the same time the water velocity was analysed in several points (depending on the size of the stream) and the stream cross-section measured to obtain volume of the water flow. Measurements in all streams were performed in time as short as possible (usually 2 – 3 days) to avoid storm events or other factors that might differentiate analysed watersheds.

Water sampling was made at the mouth of each stream. Six of the streams took their sources in other lakes (see map and Table 1). In case of 5 of these streams in April additional samples of water were taken and water flow measured at the beginning of the stream in order to determine the net flux of nutrients from the direct watershed after deduction of the inflows from the upper lake.

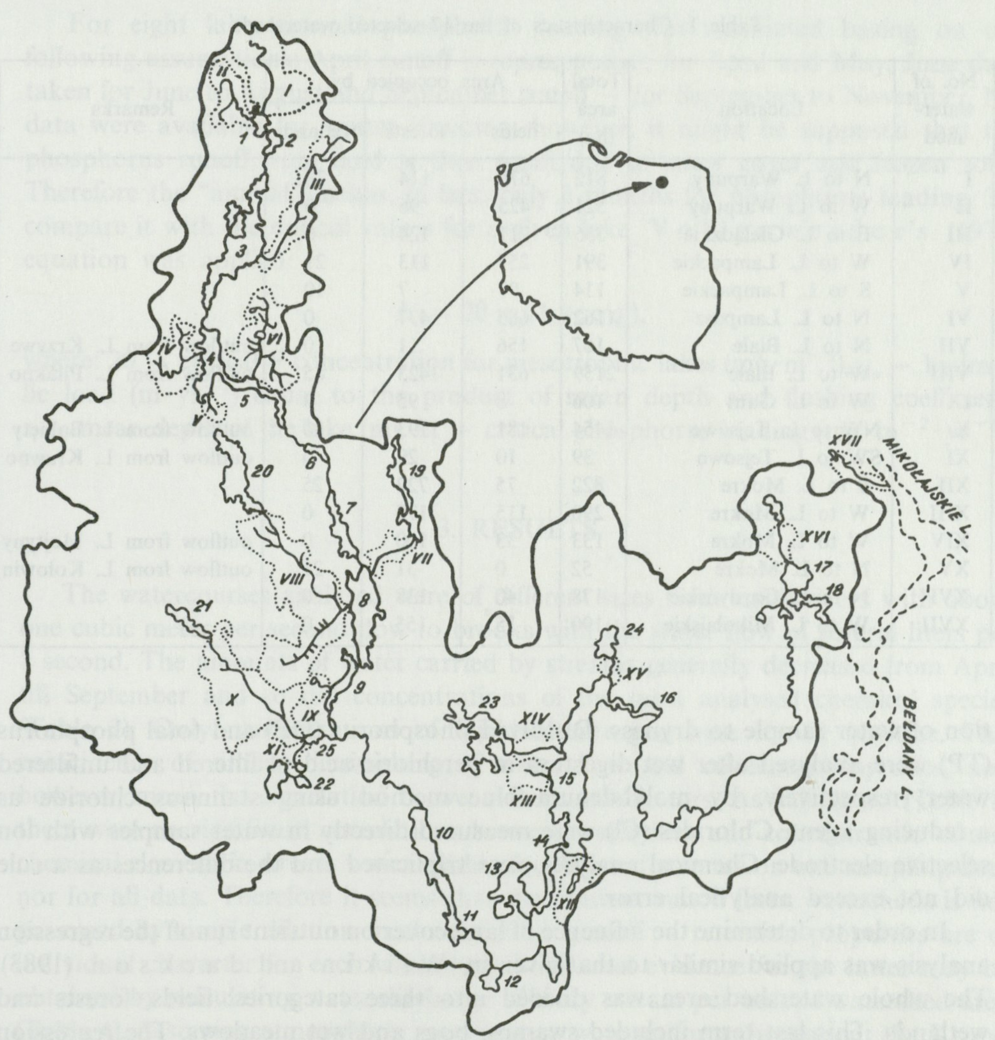

Fig. 1. Map of the Krutynia River drainage basin

Dotted line – borders of selected watersheds. I–XVII – numbers of watersheds and respective streams. Lakes: 1 – Warpuny, 2 – Zyndaki, 3 – Giełądzkie, 4 – Lampackie, 5 – Lampasz, 6 – Kujno, 7 – Dłużec, 8 – Białe, 9 – Gant, 10 – Zyzdrój Wielki, 11 – Zyzdrój Mały, 12 – Spychowskie, 13 – Zdrużno, 14 – Uplik, 15 – Mokre, 16 – Krutyńskie, 17 – Gardyńskie, 18 – Malinówko, 19 – Krzywe, 20 – Piłakno, 21 – Babięty, 22 – Krawno, 23 – Mojtyny, 24 – Kołowin, 25 – Tejsowo

Three water samples from each stream were carried to lab, mixed to produce one sample and part of it passed through Whatman GF/C filter. Suspended solids (SS) carried by stream waters were analysed gravimetrically after drying at 105°C. Dissolved Kjeldahl nitrogen (DKN) and total Kjeldahl nitrogen (TKN) were analysed in filtered and unfiltered water, respectively, by standard Kjeldahl combustion with subsequent analysis of resulting ammonia with indo-phenol blue method. Nitrate-nitrogen ($N—NO_3$) was analysed with phenyldisulphonic acid after evapora-

Table 1. Characteristics of the 17 selected watersheds

No. of watershed	Location	Total area (ha)	Area occupied by: fields	forests	wetlands	Remarks
I	N to L. Warpuny	812	670	114	28	
II	W to L. Warpuny	521	425	96	0	
III	E to L. Gielądzkie	335	211	124	0	
IV	W to L. Lampackie	391	257	113	21	
V	S to L. Lampackie	114	97	7	10	
VI	N to L. Lampasz	1162	685	477	0	
VII	N to L. Białe	167	156	11	0	outflow from L. Krzywe
VIII	W to L. Białe	2139	631	1423	85	outflow from L. Piłakno
IX	W to L. Gant	106	8	95	3	
X	NW to L. Tejsowo	1454	181	1193	80	outflow from L. Babięty
XI	SW to L. Tejsowo	39	10	29	0	outflow from L. Krawno
XII	S to L. Mokre	822	75	722	25	
XIII	W to L. Mokre	290	115	175	0	
XIV	W to L. Mokre	133	33	100	0	outflow from L. Mojtyny
XV	N to L. Mokre	52	0	31	21	outflow from L. Kołowin
XVI	N to L. Gardyńskie	178	40	138	0	
XVII	W to L. Mikołajskie	190	35	155	0	

tion of water sample to dryness. Dissolved phosphorus (DP) and total phosphorus (TP) were analysed after wet digestion in perchloric acid of filtered and unfiltered water, respectively, by molybdenum blue method using stannous chloride as a reducing agent. Chlorides (Cl) were measured directly in water samples with ion selective electrode. Chemical analyses were triplicated and the differences as a rule did not exceed analytical error.

In order to determine the influence of land cover on nutrient runoff the regression analysis was applied similar to that given in Wilkin and Jackson (1983). The whole watershed area was divided into three categories: fields, forests and wetlands. This last term included swamps, bogs and wet meadows. The regression equation was as follows:

$$y = a + bx + cz + dw$$

where: y – total load in $kg \cdot d^{-1}$, x, z, w – area of fields, forests and wetlands, respectively, in each watershed in ha, b, c, d – regression coefficients (unit runoff from respective watershed subdivisions) in $kg \cdot ha^{-1} \cdot d^{-1}$.

For the calculations only April data were taken. In case of streams VII, VIII, X, XI and XIV the loads were calculated as a difference between the discharge at the mouth of the stream and the outflow of the upper lake. Stream XV was not taken into account since it is very short (small watershed area) and thus strongly influenced by the upper lake. In this way, for each chemical species analysed, a set of 14 equations was obtained, which were calculated by matrix algebra. Statistical significance (difference from zero) of regression coefficients was checked by Student t test.

For eight lakes annual phosphorus loading was calculated basing on the following assumptions: April runoff is representative for April and May, June data taken for June to August and September runoff – for September to November. No data were available for winter situation, however, it might be supposed that the phosphorus runoff from land is then small due to snow cover and frozen soils. Therefore the "annual" means, in fact, only 8 months for phosphorus loading. To compare it with the critical values for a given lake Vollenweider's (1976) equation was applied:

$$L_c = 20 \cdot q_s(1 + z/q_s),$$

where: 20 – critical P concentration for mesotrophic lakes ($mg \cdot m^{-3}$), q_s – hydraulic load ($m \cdot yr^{-1}$) equal to the product of mean depth and flushing coefficient, z – mean depth of the lake (m), L_c – critical phosphorus loading ($mg \cdot m^{-2} \cdot yr^{-1}$).

3. RESULTS

The watercourses analysed were of different sizes from small rivers with about one cubic meter per second flow to brooks with the water flow of several liters per 1 second. The amounts of water carried by streams generally decreased from April till September and so did concentrations of the most analysed chemical species (Table 2). Only concentrations of Kjeldahl nitrogen were lowest in June. This coincidence of similar diminishing of water flow and concentrations does, not, however, mean the correlation between these two factors. As calculated (Table 3) there were no significant correlations between water flow and concentration of any chemical element in stream water neither for different streams on one sampling data nor for all data. Therefore it seems that the nutrient runoff from watersheds is not governed by simple dilution mechanisms but runoff – retention properties are of individual character for each watershed. Additional evidence for the latter may be obtained by calculating water discharge of every stream per unit of watershed area (Table 4). Assuming atmospheric precipitation were uniform throughout the Krutynia drainage basin for given sampling data (see "Methods") and excluding streams that take their beginning in the upper lakes one obtains a wide variety of water discharge per unit area of watershed, thus a different hydrological regime in each case.

Therefore it is rather total load than concentrations that should be compared to characterize the input to the lakes from land sources. Seasonal variations of total loads (Tables 5, 6, 7) generally followed the similar pattern already observed for concentrations. Streams carried the highest loads in April, then the loads decreased.

The nitrogen loads had their minima in June. In April nitrogen in stream waters occurred mostly in dissolved form. The dissolved nitrogen ($DKN + N—NO_3$) contribution to total nitrogen ($TKN + N—NO_3$) ranged between 15–87%, the average 60% in analysed streams. In June the dissolved nitrogen share averaged only 39% and in September increased again to mean value of 62%. Thus it seems that

Table 2. Range of concentrations of the analysed chemical species and water flow in 17 streams
SS – suspended solids, DKN – dissolved Kjeldahl nitrogen, TKN – total Kjeldahl nitrogen, DP – dissolved phosphorus, TP – total phosphorus

Months	SS	DKN	TKN	$N-NO_3$	DP	TP	Cl ($mg \cdot dm^{-3}$)	Water flow ($dm^3 \cdot s^{-1}$)
	$mg \cdot dm^{-3}$				$\mu g \cdot dm^{-3}$			
April	1.0–34.5	0.10–1.50	0.55–2.53	0.04–1.22	25–150	70–463	5.0–19.0	6–1214
June	2.4–30.0	0.03–0.98	0.05–2.60	–	15– 90	35–180	–	2– 807
September	0.6–17.0	0.03–5.08	0.23–6.13	–	10– 95	35–120	–	0– 729

Table 3. Coefficients of correlation between water flow and concentrations of analysed elements in stream water
For explanation of symbols see Table 2

Month	*n*	SS	DKN	TKN	$N-NO_3$	DP	TP	Cl
April	15	0.005	–0.039	0.429	–0.106	0.165	–0.039	–0.046
June	16	–0.329	–0.009	–0.130	–	–0.242	–0.305	–
September	14	–0.085	–0.066	–0.095	–	–0.291	–0.325	–
Three sampling date	45	–0.134	–0.045	0.077	–	0.118	0.078	–

Table 4. Amounts of water discharge ($dm^3 \cdot s^{-1} \cdot ha^{-1}$) of watershed drained by analysed streams

No. of stream	Water discharge		
	Apr.	June	Sept.
I	0.33	0.01	0.01
II	0.72	0.08	0.07
III	0.81	0.13	0.21
IV	0.32	0.06	0.01
V	0.22	0.17	0.18
VI	0.28	0.06	0.04
VII*	1.59	0.67	0.03
VIII*	0.17	0.08	0.08
IX	–	0.02	–
X*	0.83	0.56	0.50
XI*	7.21	–	2.18
XII	0.04	0.01	0.01
XIII	–	0.01	–
XIV*	0.68	1.40	0.74
XV*	2.13	1.52	0.94
XVI	0.25	0.14	0.06
XVII	0.03	0.13	–

*Streams fed by the upper lakes.

June decrease mainly referred to dissolved forms of nutrient, probably due to the development of vegetative cover and rapid uptake of soluble nitrogen in the watershed.

The ratio of dissolved to total phosphorus varied within the broad range (20–100%) and presented no seasonal pattern of changes. Phosphorus runoff from land depends more on sorption capacity of soils, aeration of soils and stream waters but to a less degree on the uptake by plants. Moreover, the load of phosphorus at the mouth of a stream may be influenced by sorption on sediments as the element passes along the stream. All this factors combined make any regular trends in phosphorus runoff hard to detect.

The N : P ratio in the stream loadings was high, usually near 20 resulting from the higher retention of phosphorus in soil. This effect was described by other authors (reviewed by Kajak 1980 and Procházková 1980) and can be additionally proved by the significant unit runoff of nitrogen but not phosphorus from agricultural areas as shown in Table 8.

Regression equations applied to calculate unit runoff from watershed parts of different land use gave good approximation only in case of dissolved Kjeldahl nitrogen, nitrates and chlorides (see coefficient r in Table 8) and weak correlation for suspended solids. Phosphorus runoff, again, presented no clear picture probably due to the reasons listed above which are independent on the type of land management. It must be stressed that values shown in Table 8 refer only to spring situation, summer and autumn loads of nutrients and therefore also unit runoff were

Table 5. Loads (kg · d^{-1}) of suspended solids, nitrogen, phosphorus and chlorides discharged by analysed streams in April

A–E – load at the flow of the stream (respective number in brackets) out of the upper lake. For explanation of symbols see Table 2

No. of stream	SS	DKN	TKN	$N-NO_3$	DP	TP	Cl
I	161.57	16.178	39.984	28.197	1.456	3.467	254.02
II	497.66	39.056	53.703	36.452	0.814	3.678	279.94
III	159.84	17.587	59.326	11.255	3.517	10.857	239.33
IV	376.70	7.105	25.685	11.367	1.235	4.776	207.36
V	4.32	0.432	1.102	0.259	0.162	0.259	13.82
VI	393.98	42.172	68.881	20.243	1.406	4.920	261.79
VII	187.49	17.153	45.740	19.211	2.287	2.859	281.66
VIII	109.73	10.641	22.571	22.571	2.031	3.643	258.34
IX			not analysed				
X	356.83	29.379	223.488	5.246	10.492	13.116	640.22
XI	29.28	2.425	13.339	0.970	3.638	4.559	147.74
XII	6.05	1.960	3.219	0.896	0.210	0.350	14.69
XIII			not analysed				
XIV	12.96	5.702	7.420	2.030	0.586	1.172	40.61
XV	23.33	7.174	8.608	2.678	0.717	1.081	57.02
XVI	10.37	1.559	2.844	2.494	0.221	0.487	19.87
XVII	0.86	0.130	0.363	0.166	0.026	–	–
A(VII)	13.82	3.348	9.564	1.530	0.717	1.081	103.68
B(VIII)	10.37	1.949	4.548	5.718	0.162	0.410	42.34
C(X)	163.30	49.873	91.584	9.068	6.348	9.975	589.25
D(XI)	43.20	4.482	12.830	1.391	1.824	2.551	50.98
E(XIV)	12.96	2.042	5.643	1.182	0.204	0.672	29.38

Table 6. Loads (kg · d^{-1}) of suspended solids, nitrogen and phosphorus discharged by streams in June

For explanation of symbols see Table 2

No. of stream	SS	DKN	TKN	DP	TP
I	25.06	0.069	0.112	0.043	0.078
II	42.34	0.297	0.483	0.056	0.223
III	40.61	0.111	0.186	0.316	0.669
IV	25.92	0.311	2.239	0.187	0.270
V	12.10	0.049	0.410	0.033	0.107
VI	165.89	0.442	2.101	0.221	0.221
VII	139.10	1.452	4.645	0.435	0.726
VIII	78.62	1.887	5.516	0.290	0.508
IX	1.73	0.040	0.078	0.003	0.010
X	181.44	17.431	36.954	2.092	4.183
XI			not analysed		
XII	2.59	0.847	1.884	0.069	0.104
XIII	3.46	0.043	0.251	0.014	0.023
XIV	38.88	8.839	32.141	0.723	1.286
XV	20.74	4.641	11.467	0.376	0.854
XVI	15.55	0.281	3.845	0.043	0.216
XVII	12.96	1.469	5.616	0.141	0.227

Table 7. Loads ($kg \cdot d^{-1}$) of suspended solids, nitrogen and phosphorus discharged by streams in September
For explanation of symbols see Table 2

No. of stream	SS	DKN	TKN	DP	TP
I	2.59	0.315	0.639	0.033	0.050
II	4.32	3.875	4.549	0.168	0.186
III	66.53	3.067	7.545	0.583	0.583
IV	3.46	2.195	2.648	0.037	0.052
V	29.38	1.555	2.938	0.078	0.156
VI	9.50	0.203	0.934	0.224	0.244
VII	4.32	0.812	0.842	0.007	0.022
VIII	26.78	15.513	20.389	0.591	0.886
IX			dried		
X	340.42	69.284	94.478	1.260	2.519
XI	20.74	9.180	11.383	0.147	0.294
XII	2.59	0.026	0.648	0.009	0.030
XIII			dried		
XIV	5.18	1.270	–	0.254	0.381
XV	17.28	5.842	6.689	0.149	0.191
XVI	2.59	0.475	0.950	0.043	0.056
XVII			dried		

Table 8. Regression coefficients *b*, *c*, *d* (unit runoff from fields, forests and wetlands, respectively in $kg \cdot ha^{-1} \cdot d^{-1}$) $\pm$SD and coefficient of multiple correlation *r* for the streams sampled in April

Element	*b*	*c*	*d*	*r*
SS	0.4669* ±0.1752	−0.0316 ±0.2032	−0.9425 ±3.2877	0.6447
DKN	0.0570*** ±0.0068	0.0158 ±0.0079	−0.6183*** ±0.1282	0.9509***
TKN	0.0400 ±0.04446	0.0093 ±0.0518	0.2848 ±0.8375	0.4880
$N-NO_3$	0.0456*** ±0.0074	−0.0100 ±0.0086	−0.0248 ±0.1349	0.8730***
DP	0.0003 ±0.0014	−0.0003 ±0.0017	0.0240 ±0.0267	0.4917
TP	0.0054 ±0.0035	−0.0003 ±0.0041	−0.0080 ±0.0661	0.4371
Cl	0.3885*** ±0.0808	−0.0648 ±0.0923	−0.1961 ±1.4822	0.8488**

*Significant at $\alpha = 0.05$, **significant at $\alpha = 0.01$, ***significant at $\alpha = 0.001$.

considerably smaller. If however calculate annual (or strictly 8 frost-free months) runoff basing only on spring data one obtains 13.9 kg DKN and 11.1 kg $N—NO_3$ released annually by hectare of arable fields. These values fall well within the range of $4-40$ kg $N \cdot ha^{-1} \cdot yr^{-1}$, given by Procházková (1980) as typical runoff from European and USA agricultural lands. They are, however, much higher than average 1.3 kg $N \cdot ha^{-1} \cdot yr^{-1}$ presented by Ławacz et al. (1985) for 7 watersheds in River Jorka basin (another lowland river in Masurian Lakeland). This discrepancy is probably caused by two reasons. First, Ławacz et al. (1985) data are based on streams monitored monthly since March till December while present results refer only to high spring runoff. Secondly, cited authors grouping their watersheds considered only the dominance of arable lands or, conversely, wet meadows and woods. In other words, their watersheds were still heterogenous. The regression method applied in the present paper permits to calculate runoff strictly from unit area of arable lands. If we additionally calculate the very high retention of nitrogen in wetlands (150.9 kg $DKN \cdot ha^{-1} \cdot yr^{-1}$ and 6.1 kg $N—NO_3 \cdot ha^{-1} \cdot yr^{-1}$ resulting from negative coefficient *d* in Table 8) then it appears that the runoff from heterogenous watersheds must usually be smaller than from purely arable lands.

Phosphorus annual runoff, though statistically insignificant, amounted to 0.07 $kg \cdot ha^{-1}$ of dissolved form and 1.32 $kg \cdot ha^{-1}$ of total phosphorus. This last value was probably connected with the erosion losses of particulate phosphorus during spring high waters. Nevertheless, Procházková (1980) also gave the runoff values as high as several kilogrammes of P per ha in her review. As in the case of nitrogen, phosphorus seems to be retained in wetland areas, though the absolute values are not statistically significant.

Good approximation was obtained for chloride runoff and for considerable contribution of agricultural lands to chloride discharge to waters. High runoff values (Table 8) may suggest also the permeation of liquid manure or domestic sewage to analysed streams. The results shown in Table 8 are different from those given in preliminary report (Kufel 1987) where the influence of the upper lakes was erratically not taken into account.

4. DISCUSSION

Total outflow from the analysed streams to lakes in the Krutynia River system (excluding stream XVII) amounted: in April – 3.804 $m^3 \cdot s^{-1}$, in June – 1.594 $m^3 \cdot s^{-1}$ and in September – 1.344 $m^3 \cdot s^{-1}$. These values constitute 95, 41 and 48% of the many years' average discharge for respective months (Kondracki and Mikulski 1958) of the whole Krutynia River system to Lake Bełdany. High spring ratio of runoff to discharge was obviously caused by water accumulation in snow cover. All of these data, however, point to substantial contribution of the runoff from watershed to the hydrology of the system. Thus the stream water chemistry may strongly influence nutrient budget in lakes of the system.

To evaluate that impact Vollenweider's (1976) equation was applied to

8 lakes fed by analysed streams. The annual phosphorus loadings ranged from 54 to more than 1718 kg per lake (Table 9). Considering lake morfometry actual and critical (in Vollenweider's sense) loadings can be calculated. Examination of Table 10 reveals that most affected by land phosphorus runoff were Lake Warpuny and Lake Tejsowo. Both are relatively small and shallow but differ in their flushing rates. Despite very intensive rate of water exchange Lake Tejsowo receives P loading that is nearly twice that established to be critical. Also deeper and larger Lake Gielądzkie receives phosphorus in amounts greater than permitted by Vollenweider's criteria.

It should be noted here that the calculations presented in Table 10 include only P loadings delivered by streams. Diffused seepage from lake shores, atmospheric input and other sources were not taken into account. Also the River Krutynia itself carries considerable loads. So it is possible that the total phosphorus loadings to lakes are, in fact, higher than presented in Table 10 and may approach dangerous values.

Land impact of dissolved forms of nitrogen and of chlorides was closely related to the type of land use (Table 8). Chlorides are not precipitated by any of the chemical compounds normally occurring in soil solutions, they are neither uptaken

Table 9. Amounts of phosphorus delivered by analysed streams to the lakes in three different seasons

Lake	Nos. of streams	Apr.	June $(kg \cdot d^{-1})$	Sept.	Approx. yearly (kg)
Warpuny	I, II	7.145	0.301	0.236	485.013
Gielądzkie	III	10.857	0.669	0.583	776.878
Lampackie	IV, V	5.035	0.377	0.208	360.747
Lampasz	VI	4.920	0.221	0.244	342.656
Białe	VII, VIII	6.502	1.234	0.908	592.778
Tejsowo	X, XI	17.675	4.183	2.813	1718.944
Mokre	XII–XV	2.603	2.264	0.602	421.853
Gardyńskie	XVI	0.487	0.216	0.056	54.675

Table 10. Morfometric data and comparison of critical and actual (from Table 9) phosphorus loadings delivered by streams to lakes

Lake	Mean depth (m)	Volume $(\cdot 10^3\ m^3)$	Flushing coeff. (yr^{-1})	P. loading $(mg \cdot m^{-2} \cdot yr^{-1})$ critical	P. loading $(mg \cdot m^{-2} \cdot yr^{-1})$ actual
Warpuny	3.0	1500	0.84	105	980
Gielądzkie	7.9	32800	0.34	146	187
Lampackie	9.4	26000	0.79	316	130
Lampasz	9.2	7000	2.93	854	451
Białe	9.4	35000	1.43	494	159
Tejsowo	5.8	2037	18.07	2589	4884
Mokre	13.1	104386	0.95	504	53
Gardyńskie	2.2	2341	46.74	2101	51

by stream biota. Therefore chloride loading at the outlet of the stream strictly reflects abundance of the element in the watershed. Ammonia and nitrates, on the other hand, are easily utilized by aquatic primary producers. Thus one should expect any biotic transformations of these ions during their course along the stream. Present results indicate that this was not the case in analysed streams. The sampling was performed early in the spring and, although the data on primary production in stream are not available, the results suggest that dissolved nitrogen was then transported along the stream relatively unchanged.

The interpretation of particulate nutrients runoff is even more complex. Neither suspended solids not total nitrogen and phosphorus in streams were significantly related to the type of land use (Table 8). For the River Tay basin Al-Jabbari et al. (1980a, 1980b) showed that both concentration and load of suspended solids were correlated to water discharge. This relation caused by natural erosion was applicable to River Tay and its tributaries and possible interruptions resulted only from human interference like harvesting or large excavations in the watershed (Al-Jabbari et al. 1980b). The results from streams of R. Krutynia basin did not support that pattern of suspension transport. Generally, the maximum load of suspended solids occurred in spring, it was, however, connected with the high water flow rather than with increased concentration. It seems that besides land impact also stream hydrology and morfometry may play a role in the dynamics of transport of particulate matter. The mechanisms presented above for Tay basin do not fully recognize sedimentation and resuspension in the river. These factors may be of significance in Krutynia basin where streams flow through diversified postglacial formations. Stream rapids are interchanged with deeper parts of moderate flow velocity. Such depressions and meanders provide favourable conditions for sediment settling. This mechanism was elaborated by Dorioz et al. (1988) who studied runoff from the watershed of the River Redon. During low flow river sediments (especially their small size fraction) trapped large quantities of phosphorus which were later outwashed and discharged after storm events. The results from Krutynia basin seem to support this view. The ratio of particulate phosphorus to suspended solids in stream waters was the highest during high water flow in April (1.9 $\pm$ 1.3%) while June and September values were equal to 0.7 $\pm$ 0.6% and 0.6 $\pm$ 0.6% as an average, respectively. Despite high variability it is obvious that spring high waters outwashed sediment fractions richer in phosphorus. Therefore, temporal accumulation along the watercourse may be responsible for the lack of correlation between phosphorus runoff and the type of land management observed in this paper.

To conclude it should be pointed out that soluble nutrients monitored at the mouth of the stream may reflect the relations in the watershed. This is especially true in the absence of aquatic vegetation in the stream channel. The runoff of particulate matter from land is interferred by sedimentation and temporal accumulation in the stream bed.

As was already mentioned the calculations presented here are based on the assumption that the watershed runoff is mainly represented by stream chemistry. However, in case of steep slopes on the lake shores the direct diffuse seepage may contribute to the total nutrient input to lakes. Moreover the atmospheric precipitation and air transport of dust particles (G o s z c z y ń s k a 1985) may be of significance in lakes with non-forested watersheds and relatively large area. This paper does not pretend to list all the external nutrient inputs to lakes in Krutynia River basin. It shows only that the nutrients supplied by stream waters may themselves strongly affect nutrient budget in lakes.

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5. SUMMARY

The land nutrient runoff was measured by the analysis of nutrient loadings carried by streams representing heterogenous watersheds in the Krutynia River basin. Concentrations of nutrients and total loadings decreased since April till September, only nitrogen had its minimum in June (Tables 5, 6, 7). There was no correlation between water flow and concentration of any element analysed in stream waters (Table 3).

Each watershed was divided into three categories: agricultural fields, forests and wetlands. Regression analysis revealed significant runoff of dissolved forms of nitrogen and chlorides from the unit area of agricultural parts of watersheds (Table 8). Unit runoff of dissolved nitrogen from wetlands was negative i.e. wetlands were able to retain nitrogen in significant amounts. Phosphorus runoff was not related to the subdivisions of watersheds applied in the regression analysis.

Stream waters supplied lakes with nutrients in amounts (Table 10) far exceeding permissible limits given in V o l l e n w e i d e r (1976). This was especially true for small lakes Warpuny and Tejsowo. The phosphorus loading delivered to larger and deeper Lake Gielądzkie also overcame dangerous limit.

6. POLISH SUMMARY

Spływ substancji biogennych ze zlewni mierzono analizując ładunki niesione strumieniami reprezentującymi heterogenne zlewnie w basenie Krutyni. Stężenie analizowanych substancji malało od kwietnia do września, jedynie ładunki azotu wykazywały minimum w czerwcu (tab. 5, 6, 7). Nie stwierdzono korelacji między przepływem wody a stężeniem żadnej z badanych substancji w wodzie strumieni (tab. 3).

Każdą z badanych zlewni podzielono na trzy części: pola, lasy i środowiska podmokłe. Analiza regresji ujawniła statystycznie istotny spływ rozpuszczonych form azotu i chlorków z jednostki powierzchni pól w zlewniach (tab. 8). Jednostkowy spływ rozpuszczonego azotu ze środowisk podmokłych był ujemny, tzn. obszary te zdolne były kumulować azot w znacznych ilościach. Spływy fosforu nie zależały od zastosowanych w analizie regresji podziałów zlewni.

Wody dopływów zasilały jeziora w substancje biogenne w ilościach (tab. 10) znacznie przekraczających dopuszczalne granice ustalone przez V o l l e n w e i d e r a (1976). Odnosiło się to szczególnie do niewielkich jezior Warpuny i Tejsowo. W przypadku większego Jez. Gielądzkiego ładunek fosforu dostarczany ciekami również przekraczał wielkość dopuszczalną.

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