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THE RUNOFF OF NITROGEN AND PHOSPHORUS COMPOUNDS FROM SELECTED AGRICULTURAL REGIONS IN THE VISTULA AND ODRA DRAINAGE BASINS

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Abstract

Systematic studies on the dynamics and extent of runoff of phosphorus and nitrogen compounds from selected agricultural regions in the Vistula and Odra drainage basins not possesing point pollution sources have been carried out. The data obtained permitted determination of critical conditions under which large loads of fertilizers are transported by rivers to the receiver. The size of these loads in a given region depends on moisture conditions on its area. The coefficients of the unit runoff also depend on physiography and degree of agricultural utilization of the region.

1. INTRODUCTION

In the eutrophication process of lakes and seas, important contribution has been assigned to nutrients transferred from agricultural regions to streams in the hydrologic cycle. In the literature, however, data documenting the contribution of agriculture to the total nutrient load discharged to receiving water bodies with streams are lacking. This is due to the impossibility of discrimination of pollutants derived from various sources on the one hand, and to difficulties encountered in direct determination of non-point pollutants on the other, owing to lack of a localized, continuous, and readily analyzable effluent.

In the world literature many contributions have been confined to the estimation of the runoff of nutrients from watersheds utilized by agriculture (cf., for instance, [3], [5], [8] and [21]) and to finding relationships between the magnitude of runoff and the way of utilization of a watershed (cf., for instance, [6], [17], [7]). These reports, however, provide no data for the estimation of the proportions between non-point and point pollutants in the runoff. Also the dynamics of entering of the nutrients from cultivated regions to surface waters has been poorly understood. It was studied by a few foreign researchers only ([15], [2]).

Knowledge of the loading of rivers of the Baltic watershed with non-point pollutants and the variability of their runoff is indispensable for taking proper water-economic decisions to counteract progressing degradation of the marine environment.

Table 1. Characterization of the subwatersheds

Specification	Year of study	Watershed of the river				
		Pomorka[a]		Wietcisa[b]	Wda[b]	
		Cross section Paryż	Cross section Brzyskorzystew	Cross section Skarszewy	Cross section Czarna Woda	Cross section Błędno
Surface area [km^2]		4.0	71.9	236	940	1386
Agricultural grounds [%]		98.0	93.5	70.6	30.0	26.0
Precipitation [$m^3 \cdot ha^{-1} \cdot yr^{-1}$]	I	4781	4440	5109	6809	6429
	II	5375	4499	5981	6429	6880
Runoff [$m^3 \cdot ha^{-1} \cdot yr^{-1}$]	I	1168	682	1890	1777	1825
	II	3554	1530	2234	1825	1680
Mean unit load of mineral fertilizers [kg NPK $\cdot ha^{-1}$ of watershed $\cdot yr^{-1}$]		300	270	150	40	34

a – Investigation period Nov. '77 - Oct. '79.
b – Investigation period Apr. '77 - Mar. '79.
I – data for the first annual cycle of investigations; II – data for the second annual cycle of investigations.

This work was realized during 1977 - 1979 in the Department of Water Protection, Institute of Meteorology and Water Management. Its purpose was, firstly, to determine unit runoff coefficients of nutrients from some agricultural watersheds in the Vistula and Odra drainage areas which do not possess any significant point pollution sources; secondly, to investigate factors controlling the nutrient runoff from these watersheds. The results may be useful for estimation of the contribution of agricultural non-point pollutions to total loads discharged to the sea. They enabled also estimation of critical conditions under which large loads of fertilizers were discharged from agricultural watersheds.

2. MATERIALS AND METHODS

Two river watersheds situated within two macroregions: the Grand-Poland Lake District (the Pomorka River in the upper Noteć drainage basin) and the Middle Pomerania (the Wietcisa River, a tributary of the Wierzyca River as well as the upper and middle segments of the Wda River) were selected. The drainage area of Pomorka constitutes a plain ground moraine upland cut with riverine valleys. The area is covered with moderately or poorly permeable boulder clay on which fairly fertile soil has developed. Precipitation is the lowest in Poland, mostly non-uniform. Poor resources of ground waters cause rapid lowering of their levels and curtail runoff during dry seasons. The watersheds of Wietcisa and Wda have a more diversified sculpture of the earth's surface and sandy, well permeable soils. Large resources of ground waters together with those retained in lakes cause the river supplies to be uniform and amplitudes of the water table to be small. The investigations were carried out in five subwatersheds characterized by distinct demarcations and by the absence of larger sources of point pollution. A detailed characterization of the watershed together with meteorological-hydrological conditions during the investigations is specified in Table 1.

Annual loads of nutrients flowing off the watershed areas under investigation were calculated on the basis of regressional daily loads. These loads were obtained from measurements carried out every two weeks in cross sections bounding the watersheds, a positive correlation being utilized between momentary loads and the corresponding momentary flows. The calculations were accomplished on a computer by using an AREQ programme [22].

The basic material for estimation of the dynamics of occurring of nutrients in rivers was provided by daily measurements of the levels of nitrate nitrogen and soluble phosphate phosphorus in water sampled at selected measuring sites. Further, the results of extended analyses performed once during a season were available [20]. The investigations were carried out in two full annual cycles. The determinations were run by employing methods commonly accepted for water analysis.

Hydrological data relating to daily flows in the cross sections under study were prepared by specialized Departments of the Institute. The mean daily precipitation over a particular watershed was calculated by means of the polygon method.

In studies on correlations between soil moisture storage and nutrient loads [20], the daily increase in soil moisture storage, ΔR, was calculated from the equation

$$\Delta R = P - E,$$

where P is the daily sum of precipitation in mm, and E is the daily sum of evapotranspiration in mm. Evapotranspiration was calculated on the basis of the Bac expression [1]:

$$E_{dec} = dv - 4T,$$

where E_{dec} is the decade sum of indicatory evaporation in mm;
d is the mean decade moisture deficit in mb;
v is the mean decade wind velocity in $m \cdot s^{-1}$;
T is the decade sum of total radiation in kcal.

Parameters of the equations and correlation coefficients for the relationship: volume of flow vs. nitrate concentration were calculated on a computer by using an AREL programme [4].

3. RESULTS AND DISCUSSION

3.1. THE DYNAMICS OF OCCURRENCE OF THE NITROGEN AND PHOSPHORUS COMPOUNDS IN THE STREAMS UNDER STUDY

Waters of the rivers under study belonged to clean ones; maximum values of basic pollution indicators were only occasionally and slightly higher than those admissible for waters of the first class of cleanness. An exception provided nitrate nitrogen in the Pomorka River, where the mean level of this constituent was four times as high as the admissible one ($1.5\ mg \cdot dm^{-3}$) and occasionally it attained $20\ mg \cdot dm^{-3}$ [20].

The differences in water relations between the Grand-Poland Lake District and the Middle Pomerania regions were reflected in the dynamics of variations in water pollution with substances leached from the watershed areas. The variations were more rapid and clear-cut in Pomorka. The range of concentrations, particularly of nitrates, and the r nge of flow volumes, were much larger there. The general trend and character of the variations was, however, the same in all streams. Hence, the dynamics of occurring of the nutrients was illustrated mostly by results obtained from the Pomorka River.

Fig. 1 shows variations in the concentration of the nitrate nitrogen and phosphate phosphorus in this river (cross section Paryż) in confrontation with precipitation and flow intensity. There is a great variability of the nitrate level in water. During periods of low flow intensity (the summer and early autumn periods) the level was very low ($0.1 - 1.0\ mg\ N\text{-}NO_3 \cdot dm^{-3}$) and distinctly increased with flow intensity. This phenomenon can be explained in terms of decreasing of the nitrate nitrogen level in soil water with depth [11] due to chemical and bacteriological denitrification processes [16]. Thus, during the periods of base flow the river is fed with ground waters of

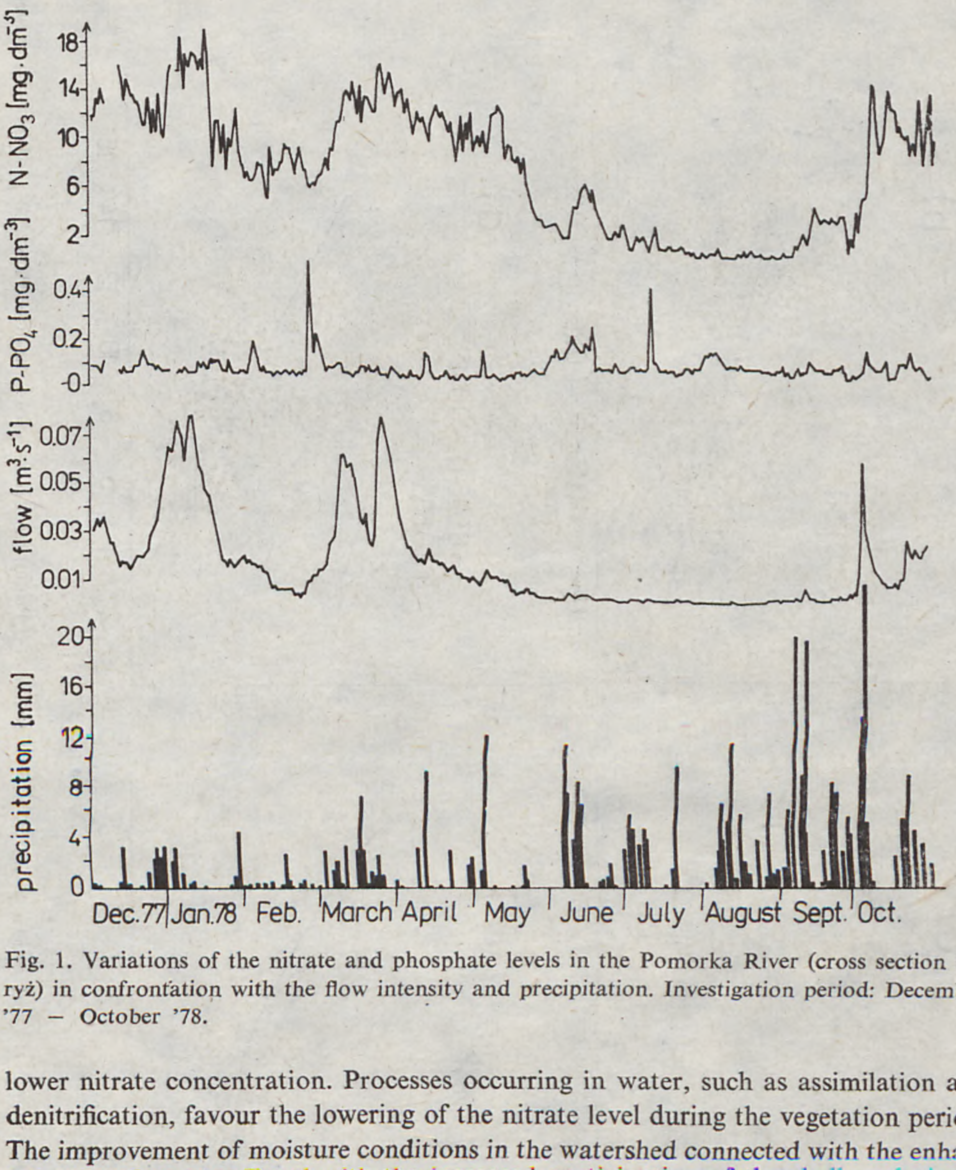

Fig. 1. Variations of the nitrate and phosphate levels in the Pomorka River (cross section P a ryż) in confrontation with the flow intensity and precipitation. Investigation period: December '77 — October '78.

lower nitrate concentration. Processes occurring in water, such as assimilation and denitrification, favour the lowering of the nitrate level during the vegetation period. The improvement of moisture conditions in the watershed connected with the enhanced subsurface runoff and with the increased participation of the shallow drainage waters in the flow contributes to increasing the nitrate nitrogen level in the river. The range of this constituent in the Pomorka River water (0.03 - 20 mg $N\text{-}NO_3 \cdot dm^{-3}$) was much larger than in the rivers of the Middle Pomerania (0.02 - 3.30 mg $N\text{-}NO_3 \cdot dm^{-3}$). The differences in the amounts of nitrates penetrating to the rivers are likely to be due largely to the different lithology of grounds and hydrological characteristics of the watershed. Important role is also played by natural fertility of soils and the load of fertilizers.

The positive correlation between the flow volume and the nitrate nitrogen level in waters of the rivers were confirmed by statistical calculations. Relationships be-

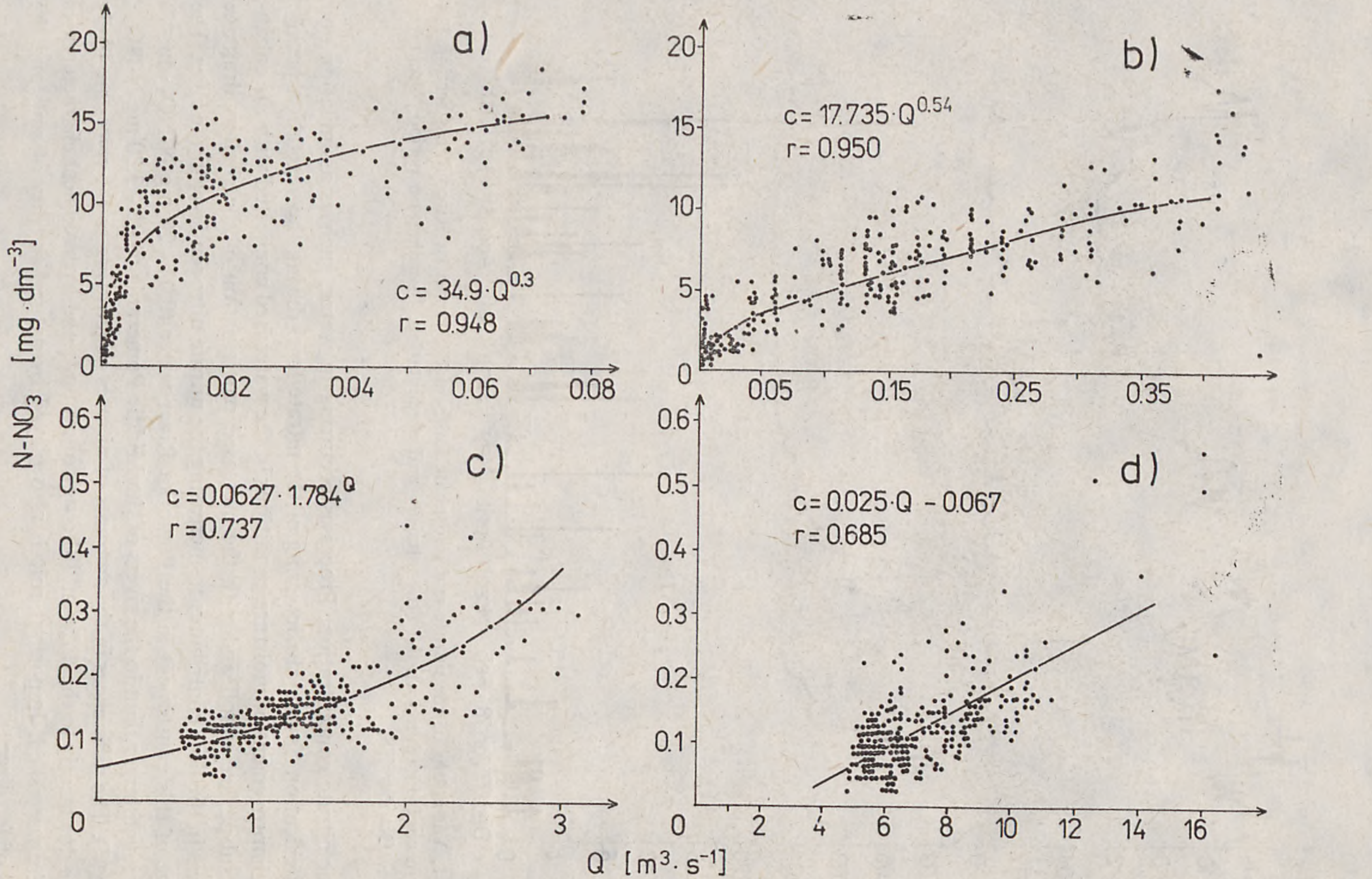

Fig. 2. Relationship between flow volume, Q, and nitrate level in the rivers; *a* – Pomorka River, cross section Paryż, *b* – Pomorka River, cross section Brzyskorzystew, *c* – Wietcisa River, *d* – Wda River.

tween these parameters are shown in Fig. 2. The high values of the correlation coefficients (0.69 - 0.95) reveal the suitability of the derived equations for the description the phenomenon. It is worth noting that the runoff during this period was mostly due to the subsurface feeding. In the case of great contribution of the surface runoff to the drainage, the concentration fails to increase proportionally to the flow. For instance, in the Pomorka River, during the flood surge in March 1979, in spite of the low volume many times higher than that in 1978, the nitrate nitrogen maintained itself on a mean level of 6 - 11 $mg \cdot dm^{-3}$. This is illustrated in Fig. 3 as a relationship between the flow rate and concentration of $N\text{-}NO_3$ established on the basis of daily measurements for the cross section Paryż during the period XI 1978 - X 1979. As it is seen, the concentration curve is broken during the period of flows due to the thawing of snow. This observation is in agreement with the results obtained by other authors (cf. Monke *et al.* [14]) who found the level of this constituent in the surface runoff to be lower than in shallow ground waters.

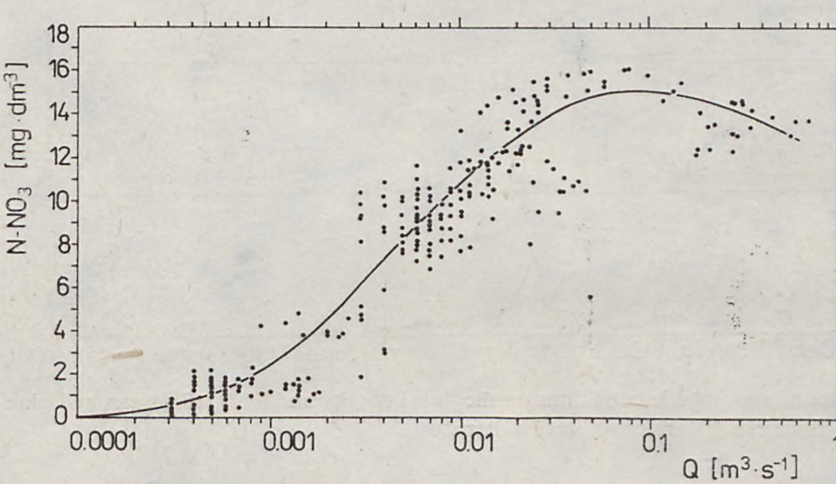

Fig. 3. Relationship between flow volume, Q, and nitrate level in the Pomorka River (cross section Paryż). Investigation period: November '78 — October '79.

The dynamics of the phosphorus compounds was unlike that of the nitrogen ones. Fig. 1 shows that, irrespective of the flow volume, the phosphate phosphorus levels oscillated roughly about the same level, peaks corresponding to heavy precipitations being regular. The high peak occurring during the last days of February is due to the appearance of first thawing waters. Similar dynamics of the occurrence was observed with other nutrients characterized by the tendency to be adsorbed on soil, such as organic phosphorus, ammonium nitrogen and organic nitrogen. Peak concentrations of these substances coincided usually with maximum flows, extremally high values being recorded in the Pomorka River during the flood in 1979. This is understandable in view of the fact that this type of compounds is transported to the river mostly on eroded soil particles together with the surface runoff and to a lesser extent with subsurface feeding. The range of their concentrations was smaller

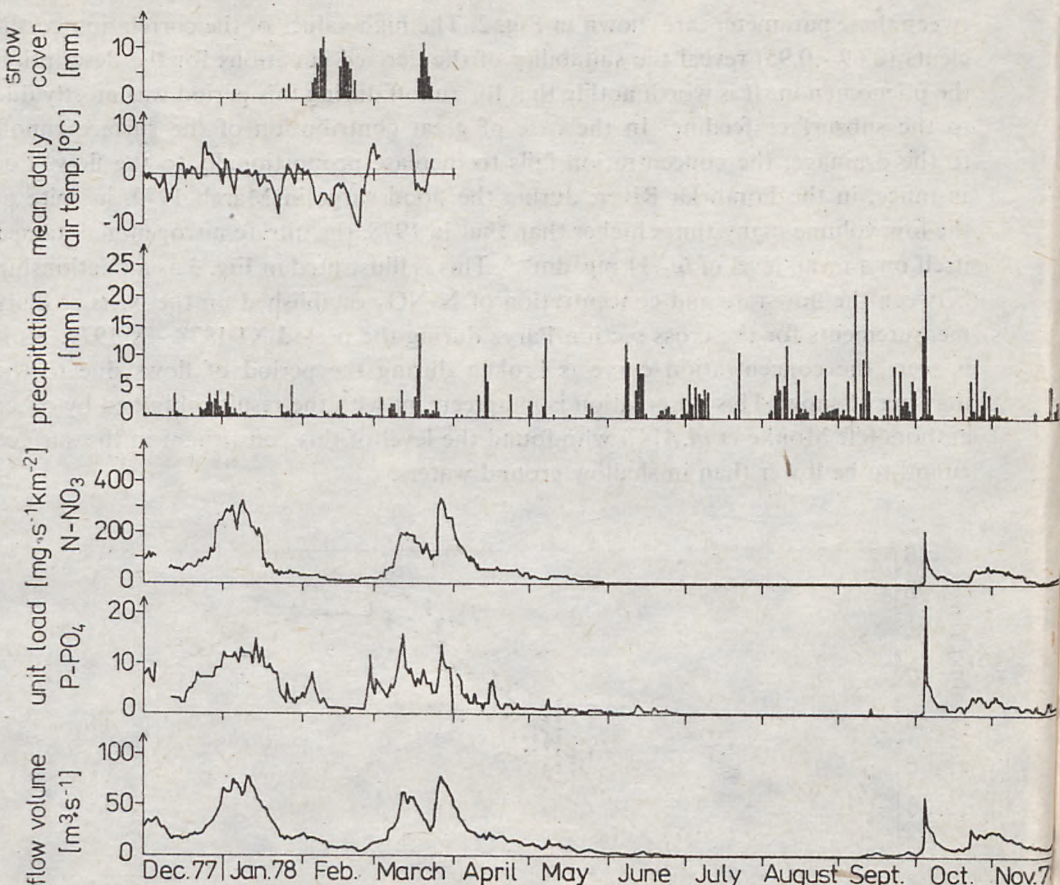

Fig. 4. Influence of atmospheric conditions on the flow intensity and loads of nitrates and phosphates in the Pomorka River (cross section Paryż).

than that of the nitrate nitrogen; the levels of the total and phosphate phosphorus in the riverine cross sections ranged from 0.06 to 0.60 and from 0.02 to 0.52 $mg \cdot dm^{-3}$ respectively, whereas that of the ammonium nitrogen from 0.02 to 2.80 $mg \cdot dm^{-3}$. The concentration of organic nitrogen fell within the range 0.10 - 1.50 $mg \cdot dm^{-3}$. This form of nitrogen constituted 1 to 60% of the mineral nitrogen content. A characteristic feature, in accordance with the described mechanisms of entering of the nutrients to water, is that the decreasing nitrate level was accompanied by an increase in the contribution of organic nitrogen to the total nitrogen.

Variations in the load, i.e. total amount of nutrients carried with river waters, followed a slightly different pattern as compared with that of the concentrations. In Fig. 4, the effect of atmospheric conditions on the flow intensity and the nitrate and phosphate loads carried by the river are shown. Also in this case, daily measurements in the cross section Paryż in the Pomorka River were utilized. There is no direct dependence between the volume of precipitation and the flow or load. The response of the flow to precipitation was different and depended on the season.

There is, however, a distinct positive correlation between the flow intensity and load of the constituents both in the case of nitrates and phosphates. It is clearly seen that the amount of nutrients carried with the river is closely related to the hydrologic cycle in the watershed. The significance of this correlation is highlighted by great values of the correlation coefficients for regression straight lines determined for the basic forms of nitrogen and phosphorus in water of the rivers. The correlation coeffi

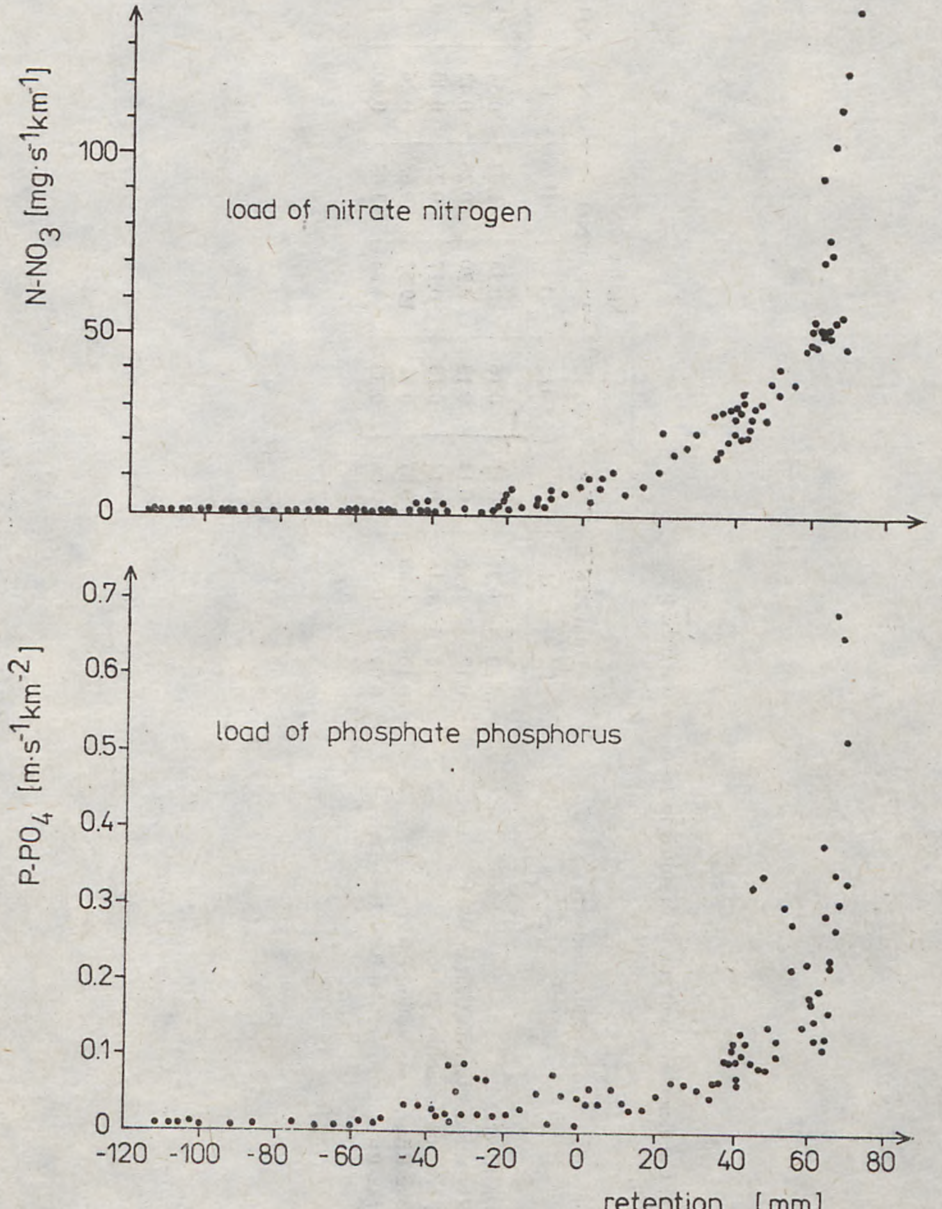

Fig. 5. Relationship between soil moisture storage and loads of nitrates and phosphates.

Table 2. Coefficients of unit runoff of nutrients from the watersheds

Subwatershed	kg·ha^{-1}·yr^{-1}									
	Total P		P – PO_4		N – NO_3		N – NH_4		Organic N	
	I	II	I	II	I	II	I	II	I	II
Wietcisa River	0.20	0.21	0.11	0.16	0.34	1.02	0.54	1.36	0.31	0.26
Wda River, cross section Czarna Woda	0.17	0.16	0.14	0.13	0.20	0.26	0.42	0.44	0.32	0.21
Wda River, cross section Błędno	0.18	0.16	0.14	0.13	0.17	0.23	0.40	0.38	0.32	0.21
Pomorka River, cross section Paryż	0.10	0.85	0.07	0.68	19.52	49.68	0.26	1.81	0.40	0.66
Pomorka River, cross section Brzyskorzystew	0.09	0.43	0.06	0.33	4.84	13.63	0.30	1.44	0.27	0.44

I – 1977/78; II – 1978/79.

cients ranged from 0.450 to 0.999, only 3% of them being lower than 0.6, and the majority (56%) exceeded 0.90 [20].

In view of the lack of a correlation between the nutrient load and precipitation, the analysis of the conditions of entering of the nutrients into water was based on the moisture storage in soil which is the outcome of interaction of the complex of atmospheric factors. Fig. 5 shows a relation between this parameter and the load of nitrates and phosphates in the Pomorka River (cross section Paryż) during the vegetation period of 1978. It was assumed that at the beginning of the season the soil had been saturated with moisture and the useful moisture storage amounted to 80 mm [13]. Moisture storage below the useful level is indicated as the negative values. As it is seen, during dry periods (moisture storage to 20 - 40 mm), the nutrient loads increased very slowly with increasing moisture storage of the soil. As soon as the soil began to attain saturation, the flow increased sharply together with the amount of the nutrients carried away. With improving moisture conditions of the soil, the subsurface feeding becomes more intense. When the moisture storage of soil attains the value of nominal retention and the surface runoff becomes significant, the nutrient loads can attain very high values.

3.2. CHARACTERIZATION OF THE UNIT RUNOFF COEFFICIENTS OF NUTRIENTS FROM THE WATERSHEDS

The coefficients of unit runoff of nutrients, expressed in kg per hectare of watershed per year, are specified in Table 2. According to the observed dynamics of the occurrence of the nutrients in the rivers, an increase in the runoff of water (Table1) was accompanied by an increase in the coefficients. A particularly striking difference was observed in the Pomorka River. For instance, in the cross section Paryż, the water runoff in the second annual cycle was three times as high. Also the runoff of the nitrate nitrogen was three times higher, whereas that of the ammonium nitrogen and phosphorus constituents was as much as 10 times higher. This is understandable in terms of a large flood surge in the spring of 1979 which caused large runoff of water and strong erosion of soil.

The coefficients of unit runoff of nutrients in the watersheds of the Middle Pomerania for the nitrate nitrogen, ammonia nitrogen and organic nitrogen ranged from 0.17 to 1.02, 0.4 to 1.36, and 0.21 to 0.32 $kg \cdot ha^{-1} \cdot yr^{-1}$, respectively whereas for the total phosphorus they ranged from 0.16 to 0.21 $kg \cdot ha^{-1} \cdot yr^{-1}$. The transport of nitrogen and phosphorus was thus almost identical as that found in Finland's rivers with watersheds utilized by agriculture, having very poor soil [7]. The unit runoff of nitrates from the watershed of the Pomorka River was much larger, amounting to 4.8 - 19.5 $kg \cdot ha^{-1} \cdot yr^{-1}$ during the first year of investigation and to 49.7 $kg \cdot ha^{-1} \cdot yr^{-1}$ during the second year. This high runoff was due to particular meteorological-hydrological conditions. This notwithstanding, it was the order of magnitude reported by the Dutch [9], American [12] and Russian [10] authors.

The estimation of the contribution of agricultural non-point sources to the total load of nutrients transported to the sea with river waters is not feasible on the basis of the selected physiographic region of the drainage area. Nevertheless, a comparison of the unit runoff coefficients for the nitrogen and phosphorus compounds of the Vistula watershed in its estuarine cross section with those of the watersheds of the Middle Pomeranian rivers (Table 3) throws light on the importance and size of the sources. Drawing conclusions from this comparison is justified by the representativeness of the region for large areas of the northern Poland and by the relatively high accuracy of annual loads calculated for the Vistula in the cross section Kiezmark (926th km of the river) on the basis of the measurements carried out twice a week [18, 19].

Table 3. Comparison of the unit runoff coefficients of selected forms of phosphorus and nitrogen in the Middle Pomeranian rivers and in the Vistula

Component [kg·ha⁻¹·yr⁻¹]	Wietcisa River		Wda River[a]		Wisła	
	I	II	I	II	I	II
$P\text{-}PO_4$	0.11	0.16	0.14	0.13	0.12	0.19
Total P	0.20	0.21	0.18	0.16	0.45	0.55
$N\text{-}NO_3$	0.34	1.02	0.18	0.25	2.16	2.38
N Kjeldahl	0.85	1.57	0.73	0.62	2.92	3.62

[a] – Mean values for the two subwatersheds.
I – 1977/78; II – 1978/79.

Table 3 shows the unit runoff of the soluble phosphate phosphorus with the Vistula to be of the same order of magnitude as that with the Pomeranian rivers, whereas the unit runoff of the total phosphorus was up to three times as high. It can thus be concluded that phosphorus occurring in the former form enters the river mostly from the watershed area, whereas other forms of phosphorus are mostly derived from point discharges. The amount of the nitrate nitrogen leached yearly from 1 hectare of the Pomeranian river watershed constituted from 8 to 40% (20% on average) of the unit load of this constituent exported with Vistula to the sea, and it was directly related to the degree of agricultural exploitation of the watershed and to the magnitude of the water runoff (Table 1). The latter factor was also important with the Kjeldahl nitrogen, while no distinct influence of the agriculture was noted. During the first year of investigations, the relations were similar to those observed for the two rivers of the Pomerania (28.5% of the Vistula load on average). Some differences emerged in the second year (43 and 17% for the Wietcisa and Wda rivers, respectively, together with differentiation of the unit runoff of water).

A similar analysis for the Odra drainage basin was not feasible due to the lack of concentration measurements of the nutrients in its waters with a frequency required for calculation of a reliable river load. This notwithstanding, an estimation of the magnitudes of the unit runoff coefficients for the Pomorka River shows that the load of nutrients washed out from a watershed intensively exploited by agriculture can be as high as, or even many times higher (nitrate nitrogen) than, the load from the point sources.

To sum up, it seems likely that point sources contribute more than non-point sources to the overall nutrient loads exported with the Vistula to the sea. This is particularly evident in the case of nitrates. This component can, however, predominate in the runoff from agricultural watersheds under conditions which favour washing out of the component from soil.

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