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PHOSPHORUS RUNOFF FROM SMALL AGRICULTURAL CATCHMENTS UNDER DIFFERENT LAND USE INTENSITY*

Andrzej Skwierawski, Katarzyna Sobczyńska-Wójcik, Małgorzata Rafałowska

Chair of Land Reclamation and Management
University of Warmia and Mazury in Olsztyn

Abstract

The study was carried out in the hydrologic year 2006 and comprised two small agricultural catchments in the Masurian Lakeland. Both catchments possessed very large water retention potential (presence of buffer zones and surface waters in the catchments) but they differed in the intensity of agricultural production.

The study has demonstrated that the concentration of phosphorus in the surface waters flowing from the catchments ranged from 0.12 to 0.43 $mg \cdot dm^{-3}$. The catchments were characterised by low indices of water overland flow (0.32-1.67 $dm^3 \cdot s^{-1} \cdot km^{-2}$), which was a decisive factor shaping the runoff of phosphorus (from 0.013 to 0.060 $kg \cdot ha^{-1} \cdot year^{-1}$. A subcatchment dewatered by a pipe drain system, which was used for comparison, had a water flow of 3.54 $dm^3 \cdot s^{-1} \cdot km^{-2}$ and exported much more phosphorus with its surface waters (0.39 $kg \cdot ha^{-1} \cdot year^{-1}$). The results obtained during our study emphasise an important role played by small landscape water retention elements in both catchments and the efficiency of buffer zones at a contact of water bodies and fields in reducing the runoff of biogenic substances, especially when agricultural production carried out on a given catchment is intensive.

Key words: phosphorus, migration of biogenic substances, water flow, agricultural catchments, biogeochemical barriers.

dr inż. Andrzej Skwierawski, Chair of Land Reclamation and Management, University of Warmia and Mazury, pl. Łódzki 2, 10-719 Olsztyn, Poland, e-mail: andore@uwm.edu.pl

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STRATY FOSFORU Z MAŁYCH ZLEWNI ROLNICZYCH O RÓŻNEJ INTENSYWNOŚCI UŻYTKOWANIA

Abstrakt

Badania prowadzono w roku hydrologicznym 2006, w dwóch małych zlewniach rolniczych położonych w obrębie Pojezierza Mazurskiego. Badane zlewnie charakteryzowały się dużymi zdolnościami retencyjnymi (obecność stref buforowych i wód powierzchniowych w zlewni) oraz zróżnicowanym poziomem intensywności rolniczego użytkowania.

Wykazano, że koncentracja fosforu w wodach odpływających z badanych zlewni rolniczych kształtowała się w zakresie 0,12÷0,43 $mg \cdot dm^{-3}$. Zlewnie charakteryzowały się niskimi wskaźnikami odpływu wody (0,32÷1,67 $dm^3 \cdot s^{-1} \cdot km^{-2}$), co w największym stopniu wpłynęło na odpływ fosforu, kształtujący się na poziomie od 0,013 do 0,060 $kg \cdot ha^{-1} \cdot rok^{-1}$. W porównawczej zlewni drenarskiej, o wskaźniku odpływu 3,54 $dm^3 \cdot s^{-1} \cdot km^{-2}$, wykazano wielokrotnie wyższy eksport fosforu z wodami – 0,39 $kg \cdot ha^{-1} \cdot rok^{-1}$. Uzyskane wartości wskazują na rolę małej retencji krajobrazowej w badanych zlewniach oraz skuteczność stref buforowych na styku wód i pól uprawnych, ograniczających odpływ biogenów, zwłaszcza w warunkach intensywnej produkcji rolniczej na obszarze zlewni.

Słowa kluczowe: fosfor, migracja biogenów, odpływ wody, zlewnie rolnicze, bariery biogeochemiczne.

INTRODUCTION

The runoff of phosphorus from drainage basins to surface waters is a serious environmental threat associated with the increasing eutrophication of water bodies (KAJAK 2001, SCHIPPERS et al. 2006). In larger hydrographic systems, owing to the gradual elimination of point pollution sources achieved by constructing and developing wastewater treatment plants in urbanised areas, the volume of phosphorus load reaching surface waters will typically depend now on the size of phosphorus runoff from agricultural catchments (EKHOLM, MITIKKA 2006). The risk of contaminating surface waters by non-point sources of pollution is most evident in farmlands under intensive agricultural practice; this effect is accompanied by a large decrease in the contribution of point sources of pollution (CARPENTER et al. 1998). Non-point pollution sources are much more difficult to reduce, hence it is important to monitor the runoff of phosphorus from agricultural drainage basins. The actual amounts of phosphorus flowing from unit surface depend on several factors, such as landscape features, type of soils, weather conditions, type and intensity of agricultural production. Considering the diversity of such conditions for different locations and their time-related variability, any attempt at evaluating the volume of phosphorus that is not based on long-term and systematic studies will be burdened with a large error, the fact that has been supported by many reports published in our country (GIERCUSZKIEWICZ-BAJTLIK 1990, KOC 1998, BAJKIEWICZ-GRABOWSKA 2002).

The objective of this study has been to determine the volume of phosphorus exported from two catchments, both characterised by a relatively low index of unit surface water runoff. The underlying hypothesis was that the export of biogenic substances from areas characterised by the surface water runoff being much lower than the average should be equally low. Another aim of the research was to compare the phosphorus runoff index values according to the intensity of agricultural use of both basins.

MATERIAL AND METHODS

The study was carried out in the hydrologic year 2006 and comprised two catchments lying in geographical region of Masurian Lakeland (Pojezierze Mazurskie). Although both objects – Sętal and Doba – can be defined as small agricultural drainage basins, they are clearly different in the intensity of agricultural production. Sętal basin is under extensive agricultural use, whereas the area drained to Dobskie Lake is at a serious risk of being polluted by agricultural points of pollution, as it is farmed rather intensively.

Sętal (Figure 1) is a subcatchment of a larger catchment of the middle Łyna River, lying 20 km north of Olsztyn. It covers about 24 km^2 and is drained by a surface stream called the Sętalska Struga. The control plane taken for our study (point 439) on this stream lies about 500 m away from its flow into the Łyna River. The study also included the drainage basin of the northern side of the Sętalska Struga (point 440). The whole basin covers 1,500 ha (Table 1), whereas the other, northern stream (nameless) drains 980 ha in the northern part of the catchment. The land utilisation structure of these objects is dominated by arable land (60%) and grassland (25%), mostly under extensive farming. In the 1990s half of the land was laid fallow. The catchment has a rather small contribution of wooded areas (10%) and a large share of surface waters (5%). Our study also comprised the tributaries of Nowe Włóki Lake (points 431A and 432A), lying in the upper part of this basin, which drained 50 and 172 ha, respectively, and consisted mainly of arable lands. All the above subcatchments are dominated by sandy loam and loamy sand soils, which were classified as soil valuation classes IVa and IVb in the Polish soil classification system.

Doba object contained three subcatchments of Dobskie Lake (Figure 1). The subcatchment designated as number 522 covered 28 ha. It contains a surface stream which flows to the main basin of Dobskie Lake near the village Doba and in its upper part is fed by pipe drains, which drain arable lands. The farmland in this catchment lies on medium compact soils (loamy sand) classified as IIIb and IV soil valuation classes. In the year of our study, the arable lands received pre-sowing mineral fertilization corresponding to 110 kg $N \cdot ha^{-1}$. In the spring and autumn of that year the fields were

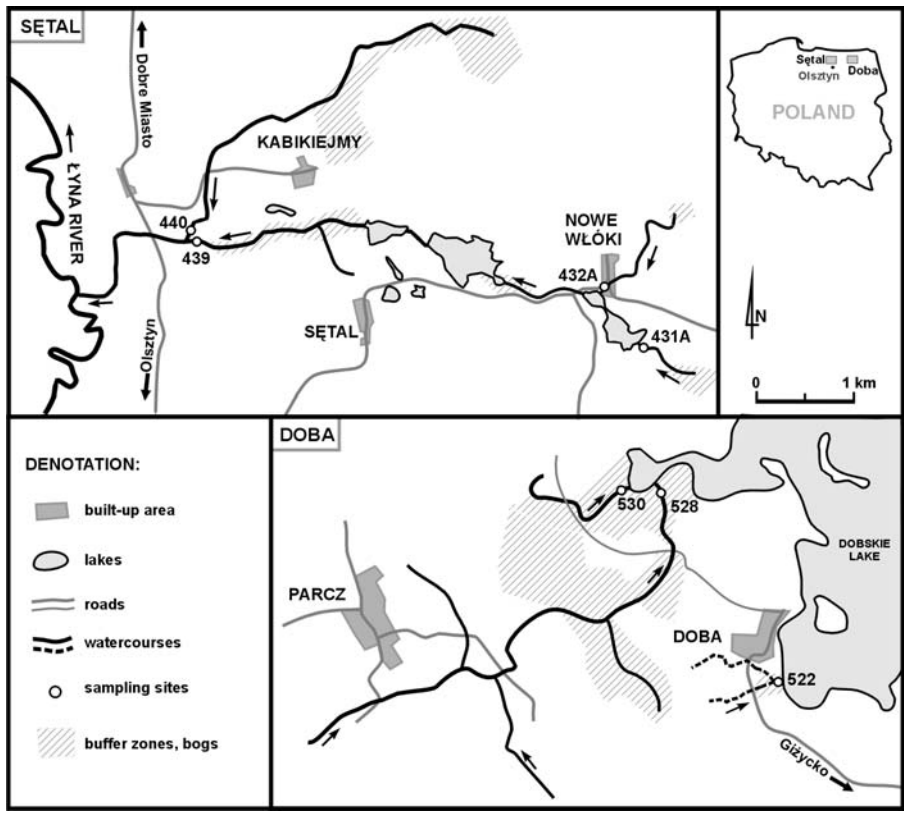

Fig. 1. Location and plans of Sętal and Doba catchments

Table 1

Basic hydrologic data of the control planes of set at the examined watercourses

Indicator	Sętal				Doba		
	431A	432A	439	440	522	528	530
Catchment area (ha)	50	172	1505	980	28	1616	109
Mean water flow ($dm^3 \cdot s^{-1}$)	0.25	0.53	23.9	3.12	0.99	12.2	0.41
Min-max flow ($dm^3 \cdot s^{-1}$)	0.0 1.9	0.0 2.9	1.6 107.3	0.8 9.7	0.3 2.9	0.0 47.8	0.0 1.7
Water overland flow ($dm^3 \cdot s^{-1} \cdot km^{-2}$)	0.50	0.31	1.67	0.32	3.54	0.75	0.38

also fertilized with FYM, in total 15 $m^3 \cdot ha^{-1}$. About 15% of the catchment area is overgrown with groups of trees, mainly near the mouth of the watercourse.

The subcatchment of point number 528 contains the recharge area of Pilwa Bay located at the westernmost end of Dobskie Lake. This surface stream drains a large area (1,616 ha) mostly (57%) covered by forest. The arable lands in this subcatchment are mainly light loamy sands (soil valuation class IVb). The arable lands received mineral fertilization (130 kg $N \cdot ha^{-1}$ and 60 kg $P \cdot ha^{-1}$) and liquid manure (15 $m^3 \cdot ha^{-1}$) with the latter divided into two rates: spring and autumn. The stream designated as number 530 dewaters the western part of the subcatchment of Pilwa Bay. The surface area of this subcatchment is 109 ha and 60% of this land is afforested. The remaining part consists of arable lands, which belong to the soil fraction of light loamy sand and receive mineral fertilization only (100 kg $N \cdot ha^{-1}$ and 60 kg $P \cdot ha^{-1}$).

Doba catchment contains an area distinguished by the Order of the Director of the Regional Water Management Board in Warsaw (*Rozporządzenie...* 2004) as being under a particularly severe ecological threat, where the phosphorus runoff from agricultural sources should be limited. This area comprises the whole basin dewatered by the pipe drains (no 522) and the eastern part of the watercourse catchment no 528.

Our study on the migration of phosphorus in the above catchments was carried out in the hydrologic year 2005/2006, which was characterised by the rainfall rated as average on a long-term scale (654 mm) and an average annual air temperature of 7.5ºC. The year had low precipitation in early spring (March, April), which reduced the thawing water runoff. Such a distribution of precipitation alongside the dry previous year meant that the first half of the year was poor in rainfall, but the annual rainfall reached the long-term average owing to heavy rains in August and September.

The study consisted of measurements of the intensity of water flows, performed weekly using an electronic meter Valeport Model 550. In each month water samples were collected from all the watercourses to perform laboratory analyses. Total phosphorus and its mineral forms were determined by spectrophometry using ammonium molybdate and tin (II) chloride.

RESULTS

The results showed that the concentration of phosphorus in the analysed water was only slightly variable, even though the research objects were highly different in their basic drainage characteristics. All the control planes of the watercourses were characterised by a low index of water outflow, ranging from 0.31 to 3.54 $dm^3 \cdot s^{-1} \cdot km^{-2}$ (Table 1). In the smaller subcatchments

drained by periodic watercourses (431A, 432A, 530), the value of this index was sometimes less than 0.5 $dm^3 \cdot s^{-1} \cdot km^{-2}$ (Table 1). The runoff in watercourse 522, supplied in its upper section by a pipe drain system, was the largest but even there the value of a unit flow was lower than an average value for lake districts, which is assessed at 5.0-6.0 $dm^3 \cdot s^{-1} \cdot km^{-2}$ (FAL 1993).

The mean annual concentrations of total phosphorus at the particular control planes oscillated within 0.12-0.43 $mg \cdot dm^{-3}$ (Table 2). The maximum phosphorus concentration was found in the watercourse carrying the water drained from heavily fertilized fields (522), but even in this case the phosphorus volume never reached the extremely high values cited in the literature (KOC, SKWIERAWSKI 2004). The waters flowing from the catchment of Dobskie Lake through the surface streams, which are separated from the fields by marshes (points 528 and 530) contained much lower concentrations of phosphorus, comparable to those in the waters from the other object, the Sętalska Struga, where the catchment surface area is under a much less intensive agricultural production.

In the annual distribution, higher levels of phosphorus occurred in most

Table 2

Mean concentrations of total phosphorus (P_{tot}) and phosphate phosphorus ($P\text{-}PO_4$) in water flowing from Setal and Doba catchments ($m \cdot dm^{-3}$)

Site number	P_{total}			$P\text{-}PO_4$		
	winter half year	summer half year	year	winter half year	summer half year	year
Sętal						
431A	0.12	0.13	0.12	0.08	0.03	0.05
432A	0.12	0.37	0.24	0.10	0.31	0.20
439	0.11	0.27	0.19	0.04	0.07	0.0
440	0.22	0.29	0.26	0.04	0.04	0.04
Doba						
522	0.48	0.36	0.43	0.11	0.19	0.14
528	0.22	0.26	0.24	0.06	0.05	0.06
530	0.15	-	0.15	0.02	-	0.02

of the sites during the summer half-year. This dependence was more pronounced for total phosphorus amounts, whereas the levels of phosphorus mineral forms were more diverse (Table 2).

The concentration of phosphate phosphorus was clearly the highest in the watercourse flowing to the northern part of Nowe Włóki Lake (432A, Table 2). The elevated levels of phosphorus in this stream should be attributed to the presence of built-up areas in this subcatchment.

While analysing the results, no statistically significant differences were discovered (using Duncan's test at $p = 0.05$) in the concentrations of phosphorus between the objects located in Sętal (on average 0.203 mg $P_{tot} \cdot dm^{-3}$) and Doba catchments (0.195 mg $P_{tot} \cdot dm^{-3}$), although the agricultural use of land in the catchment drained by the watercourses feeding Dobskie Lake was much more intensive.

As the variability of the phosphorus concentration at the particular sites was rather low, the volume of phosphorus flowing from the analysed catchments depended mainly on the flow intensity, which in both catchments was rather low, suggesting high water retention capacity. And this, in turn, was a decisive factor affecting the volume of phosphorus runoff. The unit surface phosphorus runoff in both catchments was very small, even at the control planes of those watercourses where water continued to flow throughout the whole year (439, 440).

The runoffs of P_{tot} (total phosphorus) were varied at the particular sites (Table 3). Approximately similar and all very low runoffs were found in the smallest subcatchments, dewatered by periodically flowing streams, i.e. the subcatchments of the watercourses supplying Nowe Włóki Lake (431A and 432A) and the subcatchment of the stream flowing to Pilwa Bay in Dobskie Lake (530). The runoffs of phosphorus from these subcatchments never exceeded 0.02 $kg \cdot ha^{-1} \cdot year^{-1}$. Also the northern part of the Sętalska Struga catchment (440), dewatered by a continually flowing watercourse characterised by very small annual water flow intensity variation, was determined to carry away very small volumes of phosphorus: 0.023 $kg \cdot ha^{-1} \cdot year^{-1}$ (Table 3).

Table 3

Loads of total phosphorus (P_{tot}) and phosphate phosphorus ($P\text{-}PO_4$) in water flowing from Sętal and Doba catchments ($kg \cdot ha^{-1} \cdot year^{-1}$)

Site number	P_{total}			$P\text{-}PO_4$		
	winter half year	summer half year	year	winter half year	summer half year	year
Sętal						
431A	0.012	0.008	0.020	0.008	0.003	0.011
432A	0.005	0.015	0.020	0.004	0.012	0.016
439	0.014	0.046	0.060	0.004	0.012	0.016
440	0.013	0.010	0.023	0.002	0.001	0.003
Doba						
522	0.284	0.108	0.391	0.074	0.060	0.134
528	0.044	0.015	0.058	0.010	0.007	0.017
530	0.013	-	0.013	0.002	-	0.002

The watercourse fed by the pipe drains (522), taken as a comparative object for the other sites, drained an area similar in the farming intensity of arable lands but less afforested, where the water runoff was larger but the volume of phosphorus removed with the surface water was lower by several orders than in the other objects (0.39 $kg \cdot ha^{-1} \cdot year^{-1}$). Such a value of phosphorus runoff can be regarded as typical for catchments dominated by arable lands (Koc 1998, Koc, Szymczyk 2003). The variability in the amounts of mineral phosphorus forms was shaped likewise (Table 3).

The results obtained during our study, being lower (except for site 522) than the values reported in the literature (Giercuszkiewicz-Bajtlik 1990, Koc, Szymczyk 2003), did not show any relationship between the phosphorus runoff and intensity of agricultural use of land. According to Granińska et al. (2005), the largest export of phosphorus from a catchment can occur in areas which contain a large share of farmland used intensively or big urban settlements. In contrast, the lowest loads of phosphorus in watercourses were found in drainage basins covered with extensive grasslands, marshes or lakes. The results obtained for Dobskie Lake catchment, considered to be particularly vulnerable to an influx of pollutants from agricultural sources to its watercourses, suggest that migration of phosphorus can be reduced in drainage basins which possess natural barriers to biogenic substances on their way away from a catchment. Biogeochemical barriers can affect the runoff of phosphorus mainly by halting the surface flow of waters. This is important as phosphorus carried by surface streams travels much faster than in underground waters (Archeimer, Liden 2000).

The present study has shown that the average indices of the phosphorus runoff from a catchment to its surface streams do not take into consideration the presence of buffer zones along the watercourses, which can act as biogeochemical barriers, thus limiting the influx of pollutants to waters. In one of the examined catchments, that is the drainage basin of Dobskie Lake, the watercourses which dewater the area lie in close proximity to intensively farmed lands at the total length equal 30% of their whole aggregate length. In addition, a large share of water-logged lands near the watercourses means that the concentrations and loads of phosphorus exported from the catchment were relatively small (Tables 2, 3). Under such conditions, the indices used for determination of the volumes of phosphorus loads reaching a lake from its catchment should be corrected by including the presence of areas highly capable of retaining water and accumulating matter, such as phosphorus.

CONCLUSIONS

1. The concentration of phosphorus in waters flowing from the examined agricultural catchments ranged from 0.12 to 0.43 $mg \cdot dm^{-3}$. Although the farming production in Doba catchment was intensive, no significant differences were found regarding the concentrations of phosphorus in both analysed catchments, which differed in the intensity of land use. The results indicate that land use intensity as a factor affecting the environment does not produce an unambiguous effect on the levels of phosphorus in areas under agricultural production.

2. The low levels of phosphorus runoff determined in both catchments were caused mainly by the atmospheric factors in the time period preceding our study, and by the landscape relief, which determined small values of water flow from the catchments (0.32-1.67 $dm^3 \cdot s^{-1} \cdot km^{-2}$). These conditions affected most strongly the runoff of phosphorus, which remained on a low level (0.013 to 0.060 $kg \cdot ha^{-1} \cdot year^{-1}$). The comparative catchment, partly dewatered through pipe drains, where the water flow was much higher (3.54 $dm^3 \cdot s^{-1} \cdot km^{-2}$), was found to experience a much larger phosphorus runoff via surface watercourses (0.39 $kg \cdot ha^{-1} \cdot year^{-1}$).

3. The values of the phosphorus runoff indices for the examined catchments prove that buffer zones at the contact between watercourses and fields under intensive agricultural production are very important, which means that they should be maintained and created, particularly in areas under intensive agricultural production.

REFERENCES

ARHEIMER B., LIDEN R. 2000. *Nitrogen and phosphorus concentrations from agricultural catchments – influence of spatial and temporal variables.* J. Hydrol., 227: 140-59.

BAJKIEWICZ-GRABOWSKA E. 2002. *Obieg materii w systemach rzeczno-jeziornych.* Wyd. Uniwersytetu Warszawskiego, Wydz. Geogr. i Stud. Regionalnych, s. 274.

CARPENTER S.R., CARACO N.F., CORRELL D.L., HOWARTH R.W., SHARPLEY A.N., SMITH V.H. 1998. *Nonpoint pollution of surface waters with phosphorus and nitrogen.* Ecol. Appl., 8: 559-568.

EKHOLM P., MITIKKA S. 2006. *Agricultural lakes in Finland: current water quality and trends.* Environ. Monit. Assess., 116: 111-135.

FAL B. 1993. *Zmienność odpływu z obszaru Polski w bieżącym stuleciu.* Wiad. IMGW, 16/27, 3.

GIERCUSZKIEWICZ-BAJTLIK M. 1990. *Prognozowanie zmian jakości wód stojących.* Wyd. IOŚ, Warszawa, s. 130.

GRABIŃSKA B., KOC J., SKWIERAWSKI A., RAFAŁOWSKA M., SOBCZYŃSKA-WÓJCIK K. 2005. *Wpływ użytkowania zlewni na sezonowość odpływu fosforu do wód powierzchniowych.* Cz. 2. J. Elementol., 10 (3): 693-699.

KAJAK Z. 2001. *Hydrobiologia – Limnologia. Ekosystemy wód śródlądowych*. Wyd. Nauk. PWN, Warszawa, s. 360.

Koc J. 1998. *Badania nad przemieszczaniem fosforu do wód w środowisku rolniczym.* Pr. Nauk. AE Wrocł., Chemia, 792: 84-91.

Koc J., Skwierawski A. 2004. *Fosfor w wodach obszarów rolniczych.* Zesz. Nauk. AE Wrocł., 1017: 165-182.

Koc J., Szymczyk S. 2003. *Wpływ intensyfikacji rolnictwa na odpływ fosforu do wód powierzchniowych.* Zesz. Probl. Post. Nauk Rol., 494: 191-197.

Rozporządzenie 2004. Rozporządzenie Nr 5/2004 Dyrektora RZGW w Warszawie z dnia 20 kwietnia 2004 w sprawie wprowadzenia programu działań mających na celu ograniczenie odpływu azotu ze źródeł rolniczych dla obszaru szczególnie narażonego w gminach: Giżycko i Węgorzewo.

Schippers P., van de Weerd H., de Klein J., de Jong B., Scheffer M. 2006. *Impacts of agricultural phosphorus use in catchments on shallow lake water quality: About buffers, time delays and equilibria.* Sci. Tot. Environ., 369: 280-294.