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Original Research

Surface Runoff as a Factor Determining Trophic State of Midforest Lake

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Abstract

It is generally claimed that surface runoff in forested catchments is minimal and therefore nutrient fluxes via runoff are unimportant. However, significant catchment slope inclination may promote overland water flow and, therefore, surface runoff might be responsible for transferring important nutrient loads to the lake. It was found that surface runoff waters within the catchment of Piaseczno Małe Lake have low pH (4.7-5.6), brown colour (max. 240 mgPt·dm^{-3}), and high concentrations of dissolved organic carbon (max. ca 100 mgC·dm^{-3}) – a major component of humic acids. Moreover, considerably high concentrations of biogenic substances were noted. Compared to beech-growing areas, surface runoff from pine forests contained higher concentrations of organic carbon, but lower concentrations of biogenic substances – differences were statistically significant. Similar tendencies were observed in the laboratory experiment. Moreover, the release of chemical substances from forest litter was found to be rapid. The most significant increase in nitrogen and phosphorus ions concentration and water colour and a decrease of pH were observed after the first hour of the experiment. Fluctuations of the colour and pH of the lake water (with the most intense brown colour and the lowest pH of the lake water observed in the periods of the highest rainfall and surface runoffs) indicate a significant role of surface runoff in the determination of the dystrophic condition of Piaseczno Małe Lake.

Keywords: forest litter, nitrogen, phosphorus, humification, overland flow

Introduction

Over the last years, climate variations have caused unusual weather conditions in Europe [1]. In recent decades, an increase in average air temperature and a decrease in precipitation have been observed in the Pomerania and Wielkopolska regions of Poland. Moreover, an increase in heavy rainfalls in the annual precipitation balance has been noted [2]. Rain squalls cause saturation of the upper part of soils and an increase of flow through the upper organic soil horizons [3]. In forest ecosystems, the input and output of essential nutrients are relatively small, compared with their total amount cycled within the system [4]. However, the elements exported from wooded catchments may affect the functioning of surface waters. Surface runoff is one of the diffused sources of export of elements and chemical substances to water bodies [5]. With overland flow, significant loads of nitrogen [6, 7], phosphorus [8, 9], and organic matter [10, 11] can be transported from the catchment to fresh water. The quality and quantity of surface runoff waters depend on many factors. One of the most important is the morphology of the catchment and the degree of anthropopression. The most significant loads of

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nutrients are exported from agriculturally used catchments [7, 12, 13]; as a result, surface runoff from agricultural land is a contributor to accelerated eutrophication in lakes and rivers [14]. However, some studies show that forested catchment can also be a source of significant loads of nutrients [15]. As the runoff from wooded catchments contains large loads of organic matter [4, 16], it might be responsible for dystrophication of surface waters [3, 17].

An important factor controlling the quantity of the exported chemical substances is the inclination of catchment slopes: the more steep the slopes are, the greater export of substances occurs [18]. Mountain catchments with steep slopes may export higher loads of nutrients than lowland catchments [19]. Moreover, the large inclination of catchment slopes may contribute to the elution of upper layers of soil or forest litter into the lakes [20]. The type of phytocoenosis covering the catchment plays a fundamental role in forming the physico-chemical properties of surface runoff [21, 22].

The aim of our study was to estimate the overland transfer of chemical substances from a wooded catchment, and to determine the impact of phytocoenosis on the physicochemical properties of the surface runoff. We also attempted to find out whether surface runoff was responsible for the dystrophic condition of Piaseczno Małe Lake.

Study Area

The Lake

Piaseczno Małe Lake is located in the eastern part of Drawieński National Park with at latitude and longitude of 53º07,4' N and 16º00,0' E, respectively. It is a non-throughflow lake with a relatively small surface area (8 ha) and depth (mean 3.2 m, max 6.8 m) elevated 62 m a.s.l.

The lake shows visible signs of dystrophia. Its water is characterized by low acidicity, high colour, and low conductivity, as well as high concentrations of dissolved organic carbon (DOC), the main component of humid acids. High concentrations of biogenic substances, nitrogen and phosphorus, especially in subbottom waters, were found [23]. However, they seem to be complexed by humid acids and are mostly unavailable for autotrophic organisms. In the bottom area deoxidation is observed due to the intense (yet slow, owing to low acidity) processes of decomposition of organic matter. Taking into account the morphometric features of the catchment area (large slope inclinations), it seems that surface runoff is one of the major components of the water balance of the studied lake. As Joniak and Kraska [23] claim, the lower level of the groundwater in the basin in relation to the water surface indicates a limited supply of groundwater.

The Catchment Area

The catchment area of Piaseczno Małe covers 21.6 ha. It is 2.7 times bigger than the lake's surface. It is entirely covered by forests. Eighty per cent of the area is covered by scotch pine (*Pinus silvestris* L.), whereas the remaining 20% is covered by European beech (*Fagus sylvatica* L.). Coniferous and deciduous grown areas are clearly divided.

The catchment area is dominated by podzolic soils. Most of the catchment area is built of medium permeable soils and gravel sands. An important feature determining the strong influence of the catchment area on Piaseczno Małe are the significant inclinations of the slopes (up to 40º), stimulating surface runoff and increasing the erosion of soils.

Methods

Field Procedures

Overland flow was collected from two characteristic points of the Piaseczno Małe catchment area. Station A was located on a catchment slope mainly covered by pine, and station B was located on a slope with a prevalence of beech. At each station, two surface runoff water samplers were installed. In 2006-07 the physicochemical properties of surface runoff waters and lake waters were investigated. Water samples were collected after each rain event and during spring thaw. Simultaneously, samples of surface water from the lake were analyzed. Meteorological data were collected from Drawieński National Park meteorological station in Rogoźnica, located 5 km from study site.

Experimental Procedures

The investigated material consisting of forest litter was collected from stations located near the runoff water samplers, first on the slope covered by scotch pine, and then on the slope with a prevalence of European beech. The litter was collected from the surface of 1 m^2 and dried in a dark place at a temperature of 20ºC. Afterward, 150 g samples of pine and beech litter were placed in separate water tanks and flooded with 20 dm^3 of distilled water of known parameters (pH=6.5; conductivity 2 $\mu Sm\cdot cm^{-1}$; total N=0 $mg\cdot dm^{-3}$, total P=0 mg/dm^{-3} DOC=0 $mg\cdot dm^{-3}$). For 10 days, 500 ml samples of water were collected and subjected to further physicochemical analyses. On the first day, samples were collected three times: after 1 h, 3 h, and after 6 h from the start of the experiment. Acidity, conductivity and colour of sampled water were measured and concentrations of mineral nitrogen, total phosphorus, and orthophosphates were investigated. The losses of water taken for analysis were replenished with distilled water. Water in tanks was constantly aerated with aquarium pumps during the whole experimental period. The method was based on procedures proposed by Zieliński et al. [22].

Analyses of the physicochemical properties of water samples were made according to Standard Methods for the Examination of Waters and Wastewaters (1992). Electrical conductivity and pH of water were measured using YSI 556 Multiparameter Instrument. Determination of concentration of organic carbon was made using a SHIMAZU TOC -5000 A analyzer.

Table 1. Mean values (±SE, n=18) of several physico-chemical parameters in two thermal layers of Piaseczno Małe Lake.

Parameter	unit	Epilimnia	Metalimnia
Color	[$mgPt \cdot dm^{-3}$]	25±1.9	64±0.6
Secchi depth	[m]	2.6±0.5	-
pH		6.4	5.92
Dissolved oxygen	[$mgO_2 \cdot dm^{-3}$]	7.8±1.2	2.3±1.1
BOD_5	[$mgO_2 \cdot dm^{-3}$]	1.1±0.1	5.2±1.4
COD_{KMnO4}	[$mgO_2 \cdot dm^{-3}$]	15.2±2.4	21±6.5
Nitrogen [$mgN \cdot dm^{-3}$]	NH_4	0.2±0.03	1±0.04
	NO_2	n.d.	n.d.
	NO_3	0.6±0.04	0.5±0.02
	organic	1.2±0.1	1.8±0.07
Orthophosphates	[$mgP \cdot dm^{-3}$]	0.13±.0.01	0.18±0.01
Total phosphorus	[$mgP \cdot dm^{-3}$]	0.22±0.05	0.29±0.01
Conductivity	[$\mu Sm \cdot cm^{-1}$]	70±2.2	90±1.3
DOC	[$mgC \cdot dm^{-3}$]	14.6±2.1	21.2±2.3
Chlorophyll	[$\mu g \cdot dm^{-3}$]	4.5±0.6	93.7±20.2

Results

Field Investigations

The results of our investigations confirm earlier data that Piaseczno Małe Lake is a dystrophic reservoir. Its water is characterized by low acidity (pH<6.5), low conductivity, and brown color caused by high concentrations of dissolved organic carbon (DOC). High concentrations of nitrogen and phosphorus in lake waters were found (Table 1).

The characteristic features of the surface runoff occurring in the Piaseczno Małe catchment included high concentrations of dissolved organic carbon (Table 2), an intensive brown color, the acid reaction (pH<6.5), and low conductivity (approximately 50 $\mu Sm \cdot cm^{-1}$). Moreover, high concentrations of nitrogen and phosphorus were found in overlandflow waters. Surface runoff waters contained approximately 7 mg of total nitrogen (with a prevalence of mineral nitrogen) and approximately 0.4 mg of total phosphorus per liter.

It was also found that the vegetation cover of the catchment slopes had a significant influence on the physico-chemical properties of surface runoff. Runoff from the catchment covered by pine contained almost 30% higher concentrations of ammonium nitrogen and about 40% higher concentrations of dissolved organic carbon, more intensive brown colour, and lower pH and conductivity. On the other hand, the waters of surface runoff occurring on the slopes overgrown by beech had significantly higher concentrations of organic nitrogen and nitrates, orthophosphates and calcium. Mean concentration of total phosphorus in the surface runoff was approximately 20% higher at station B, but the difference between the stations was statistically insignificant. For most of the analyzed parameters, the differences between locations were statistically significant (Table 2). We did not find any statistical correlations between the intensity of precipitation (and, accordingly, the intensity of surface runoff) and the dynamics of leaching of chemical substances from the catchment by runoff. However, the highest concentrations of chemical elements and highest values of water parameters were recorded in periods of increased runoff. Particularly high concentrations of nitrogen, phosphorus and dissolved organic carbon

Table 2. Mean values (±SE, n=19) of selected physico-chemical parameters of surface runoff waters and statistical significance of the differences between sampling stations – U Mann test.

Parameter	Unit	Coniferous	Deciduous	U-Mann test
Color	$mgPt \cdot dm^{-3}$	243.6±74.4	177.8±45.2	n.s.
COD	$mgO \cdot dm^{-3}$	145.2±19.8	107.8±10.2	**
Calcium	$mgCa \cdot dm^{-3}$	4.9±0.85	6.8±0.65	***
Orthophosphates	$mgP \cdot dm^{-3}$	0.2±0.06	0.3±0.06	*
Total phosphorus	$mgP \cdot dm^{-3}$	0.36±0.15	0.47±0.09	n.s.
N org	$mgN \cdot dm^{-3}$	2.2±0.85	3.98±0.12	**
$N\text{-}NH_4$	$mgN \cdot dm^{-3}$	3.7±1.1	2.78±0.98	*
$N\text{-}NO_3$	$mgN \cdot dm^{-3}$	0.9±0.07	2.7±0.19	***
$N\text{-}NO_2$	$mgN \cdot dm^{-3}$	0.03±0.02	0.02±0.01	n.s.
DOC	$mgC \cdot dm^{-3}$	65.3±12.8	48.3±10.7	**
pH		5.04	5.56	*
Conductivity	$mSm \cdot cm^{-1}$	75.8±16.8	97.3±19.3	*

n.s. –non significant, * - p<0.05, **- p<0.01, *** p<0.001

were observed in the surface runoff occurring during snow melting. As far as organic nitrogen is concerned, the concentrations noted in the flowing water at both stations during snow melting and heavy rainfalls increased by a factor of two compared to average. In the periods of intensive overland flow, the maximum concentrations of mineral forms of nitrogen, total phosphorus, orthophosphates, and dissolved organic carbon were also observed (Fig. 1). As far as mineral nitrogen is concerned, the highest concentration during intensive surface runoff was primarily evident at the coniferous station. Concentrations reported here during the melting of snowpack and heavy rainfall reached more than 11 mgN·dm^{-3}, while the mean concentration during the remaining part of the studied period was approximately 4 mgN·dm^{-3}. Similar fluctuations of their concentrations were recorded for both ammonium and nitrate. At station B, we also reported high concentrations of mineral nitrogen during the snow melt, although the increases were not as high as those recorded at the coniferous station (Fig. 1). As far as total phosphorus is concerned, the maximum concentrations noted during the melting of snowpack or intensive rains were nearly five times higher than average. Also, the highest concentrations of orthophosphates were observed in the periods of increased runoff, amounting to 0.425 mgP·dm^{-3} at

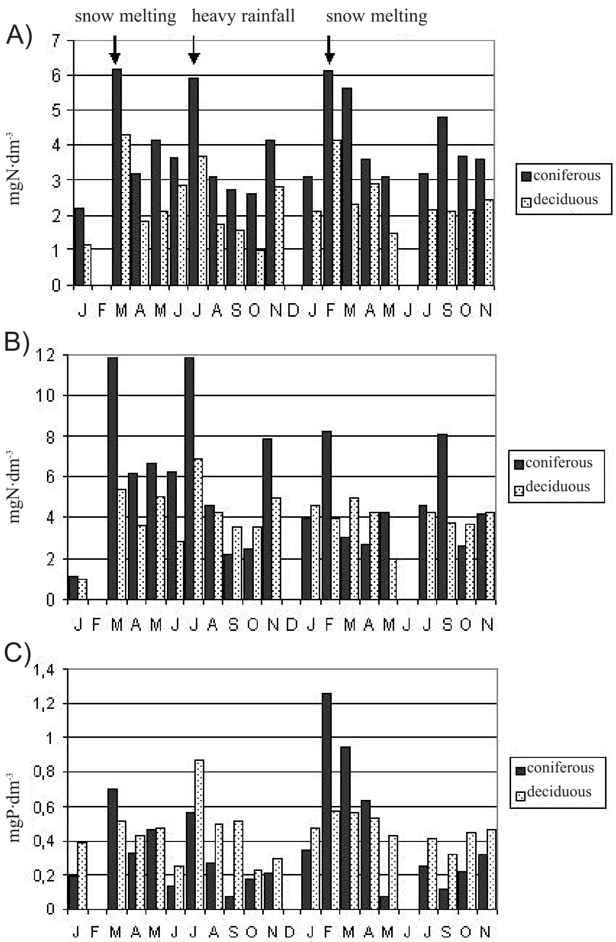

Fig. 1. Monthly variation in nutrient concentration in the surface runoff from Piaseczno Małe Lake catchment (A – organic nitrogen, B – mineral nitrogen, C – total phosphorus).

the coniferous station (during snow melting) and 0.56 mgP·dm^{-3} at the deciduous station (after heavy rain). Significant variations of the DOC concentration in surface runoff were also noted. The maximal concentration of DOC reached 101 mgC·dm^{-3} at station A, and almost 78 mgC·dm^{-3} at station B during the snow melting, and the minimal – in both locations of approximately 20 mgC·dm^{-3} – in the summer. It was also recorded that the increase of organic carbon concentration was accompanied by a decrease in the pH of surface runoff waters and an increase in color.

Laboratory Experiment

The results of the laboratory experiments correspond with the results of the surface runoff investigations. In the case of all investigated parameters and both types of litter, the most conspicuous changes were observed during the first hours of the experiment (Fig. 2). However, pine and beech litter affected the physicochemical properties of water in different ways. Both of them strongly decreased water acidity. Acidity was more decreased by pine litter (U Mann test, $p<0.001$), the pH value in the range of 3.35-4.1. Acidity of water with beech litter was in the range of pH 4.2-5.15. Fundamental differences were observed in conductivity values. The conductivity of the water with beech litter was twice as high as that of the water with pine litter. Constant increase in the mineral nitrogen content was observed both in the water with pine litter and in the water with beech litter. Slightly higher values were leached from beech litter. Nitrite ions had the least participation, ammonia ions – the highest. Statistically more nitrate ions (U Mann test, $p<0.05$) were leached from pine litter. Statistically more nitrite ions (U Mann test, $p<0.001$) were leached from beech litter. Ammonia ions were released faster from beech litter. Statistically significant differences were observed in total phosphorus release. The highest values were leached from beech litter (U Mann test, $p<0.001$). Higher concentrations of DOC were observed in the water with pine litter, which was followed by higher values of water color – mean 207 mgPt·dm^{3} for coniferous litter – mean 138 mgPt·dm^{3} for deciduous litter. However, the highest concentrations of dissolved organic carbon were noted after 48 hours of litter immersion, and subsequently (particularly in the case of pine liter) the concentrations of DOC slightly decreased (Fig. 2). Based on the obtained results, it was calculated that during the experiment, one gram of coniferous litter released into the water over 7 mg of organic carbon, nearly 0.3 mg of mineral nitrogen and a little more than 0.01 mg of phosphorus. By contrast, beech litter released smaller amounts of organic carbon but greater amounts of biogenic substances (Table 3).

Upon analysis of the dynamics of physicochemical properties of waters of Lake Piaseczno Małe, we noted that the highest concentrations of dissolved organic carbon (25.2 mgC·dm^{-3} against the annual average of 14.6 C·dm^{-3}) and the most intensive brown color of water (42 mgPt·dm^{-3} against the annual average of 25 mgPt·dm^{-3}) occurred after periods of increased surface runoff. Similar fluctuations were found for the pH of lake water – after intense rainfall, the epilimnic water pH value fell below 6.5. We found a statistically significant negative correlation between the intensity of precipitation and hence surface runoff, and epilimnic water acidity ($r=-0.77$, $p<0.05$). In periods of increased runoff we observed increased concentrations of biogenic elements in the epilimnic waters of the lake.

Discussion

Although overland flow is an episodic phenomenon, it may be an important part of the water balance of a water body [16].

We noticed that the runoff waters were characterized by high concentrations of dissolved organic carbon. Upon comparison of the results from the sampling stations, we noted that surface runoff from pine forest contained higher concentrations of organic carbon than the runoff from beech forest, and the difference was statistically significant. Higher concentrations of organic carbon in the surface runoff from coniferous locations compared with that from deciduous locations have been previously observed [17, 24]. Those observations were confirmed by the results of the laboratory experiment - significantly higher concentrations of DOC were leached from pine litter. Zieliński et al. [22] and Hongve [21] observed higher concentrations of

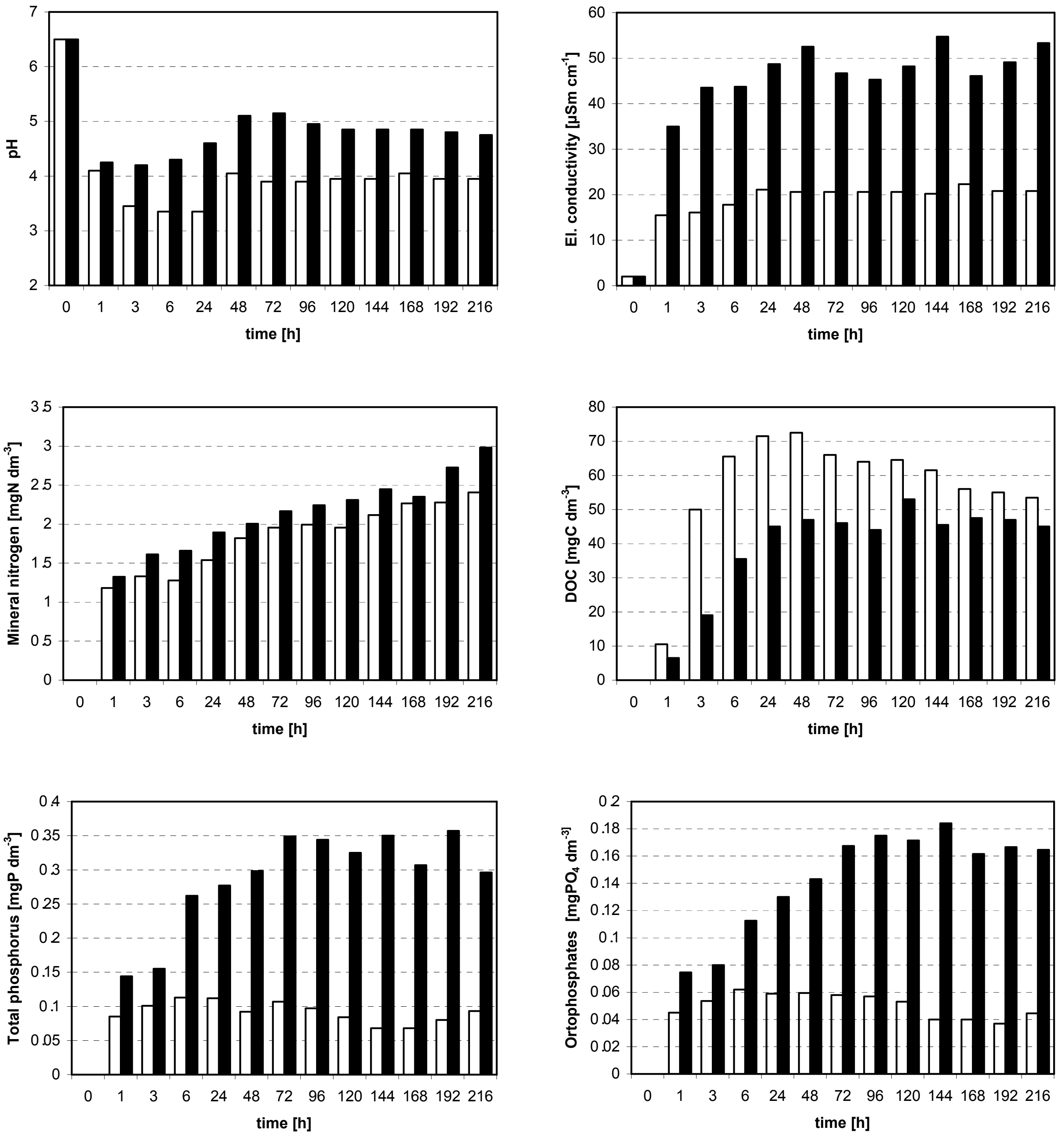

Fig. 2. Changes of acidity, conductivity, mineral nitrogen, dissolved organic carbon, total phosphorus, and orthophosphate values in water with pine and beech litter. (white blocks – coniferous litter, black blocks – deciduous litter.

DOC from deciduous litter. On the other hand, Strobel et al. [11] noted larger participation of DOC in surface parts of soils overgrown by coniferous species. The reason underlying those differences seems to be the different species of deciduous and coniferous trees taken into consideration by Zielinski, and different methods used by Hongve. Seasonal dynamics of DOC elution by the surface runoff shows significant peaks during snowmelt and intensive rainfalls. Such fluctuations have already been recorded in earlier investigations [10, 16, 21]. High concentrations of DOC have directly contributed to high values of water colour and a decrease in water pH. Concentrations of DOC noted in overland flow have been comparable to the content of DOC in the high and transitional bog waters , which are regarded as the main source of DOC incoming to the freshwaters and as the main factor contributing to lake dystrophication [24]. Therefore, we are of the opinion that the surface runoff from wooded catchment is a factor underlying humification of Lake Piaseczno Małe. This can be supported by the fact that we found strong negative correlation between precipitation and runoff, and acidity of the waters of Piaseczno Małe. Moreover, we noted that in periods following intense surface runoff the lake water had the highest concentration of DOC and the most intensive brown color. Such an impact of the surface runoff on chemical and physical properties of lake waters has been observed on other small humic lakes [16].

Concentrations of biogenic elements N and P, transported with the runoff from the investigated catchment were relatively high (Table 3) and exceeded the values recorded for most Polish forests and even agricultural-forest catchments. It seems that this may be caused by the inclination of steep slopes, which promotes water erosion [25]. Nitrogen and phosphorus concentrations in the surface runoff from forest catchments similar to those determined in our investigations have been recorded by Miller et al. [26]. The major factor affecting the concentration of biogenic elements in the surface runoff waters was the intensity of precipitation and runoff. The highest concentrations of nitrogen and phosphorus in runoff waters were observed after gusty rain and especially during snow melt. The highest concentrations of nitrogen and phosphorus in overland flow during snowmelt have been observed by Lewis et al. [27] and Sickman et al. [20]. As proposed by Fitzhugh et al. [28], the reason for this trend may be the fact that soil freezing events may increase the rates of N and P loss, with potential effects on soil N and P availability, ecosystem productivity, and surface eutrophication.

We also found that the contents of nitrogen and phosphorus in surface runoff were significantly different between the stations. Runoff waters from the slopes covered by beech were characterized by approximately 50% higher concentration of total nitrogen than the water from the slopes with a prevalence of pine. At station B, we found higher concentrations of nitrate nitrogen (about 60%) and organic nitrogen (about 40%). By contrast, amonium nitrogen was 40% higher on the slope overgrown by pine. The significant differences in the share of NH_4 and NO_3 in the total pool of mineral nitrogen at the investigated stations can be explained by the differences in the acidity of runoff water. Increased acidity of water on the slope with the prevalence of pine reduces the oxidation of ammonia, due to the limitation of the activity of nitrifying bacteria [29]. Unlike in the case of the slope with coniferous trees (station A), water flowing down a slope overgrown by deciduous trees (station B) also contained higher amounts of phosphorus. Especially large, statistically significant differences (Table 3) of approximately 25% were found in the concentrations of dissolved reactive phosphorus. Swank [30] has obtained very similar results as regards the participation of various forms of nitrogen in surface runoff from deciduous and coniferous forests. Zielinski [22] has also noted that the coniferous litter releases larger quantities of ammonium nitrogen in comparison with deciduous litter. The results of the laboratory experiment showed that beech litter enriched the water with considerably higher values of biogenic compounds: total nitrogen and phosphorus. Lower concentrations of nitrogen and phosphorus found in surface runoff on the slopes covered with pine are probably associated with a small pool of those elements in pine detritus. This species withdraws a large part of the chemicals from the needles before they fall down [31]. According to Malkonen [32], the concentrations of nitrogen and phosphorus, as well as of the majority of other ions in the needles, decreases even tenfold before they fall down. This phenomenon may also explain the lower electrolytic conductivity of runoff water found on slopes overgrown by pine (Fig. 1).

Table 3. Release of chemical substances from 1 g of investigated forest litters.

Parameter	Unit	Litter	
		pine	beech
NH_4	mg N	0.197	0.245
NO_2	mg N	0.00066	0.01
NO_3	mg N	0.047	0.029
$P_{tot.}$	mg P	0.012	0.047
PO_4	mg P	0.006	0.019
DOC	mg C	7.6	5.3

Blowing out of plant detritus or washing out of forest litter during heavy rainfalls can also deliver considerable loads of nitrogen, phosphorus, and carbon to the lake water. During investigations, significant biomass of forest detritus lining the bottom in the littoral zone of Piaseczno Małe was observed (unpublished data). It was noted that the leaching of chemical substances from litters was very fast. This finding is contradictory to the results of numerous studies [4, 21], where the authors have observed a relatively slow release of nutrients from plant detritus. However, in those studies the authors have used fresh plant detritus, which slowly releases nutrients and other elements during gradual decomposition. In fact, chemical compounds in the forest floor leachate are derived not only from recent litter but also from older organic matter in the lower forest floor horizons [33].

Conclusions

- Surface runoff from wooded catchments is an important factor affecting the trophic state of the investigated water body. Overland flow supplies water bodies with large loads of nutrients and organic matter.
- The quality of the surface runoff depends on the plants covering the catchment. Runoff from coniferous forests is characterized by higher concentrations of dissolved organic carbon, while runoff from deciduous forests is richer in biogenic elements.
- In cases of blowing or flushing of forest detritus, it may be an important source of nitrogen, phosphorus, and organic matter for the lake. The release of chemical compounds from forest litter is rapid.

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