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Editor's choice

Catchment vegetation can trigger lake dystrophy through changes in runoff water quality

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Abstract – Surface runoff can supply lakes with a variety of chemical substances – their type and quantity may significantly vary and depend on the characteristics of the catchment area: geomorphology, phytocoenosis type and degree of human impact. In this study we investigated the physicochemical properties of the surface runoff water collected from the wooded catchment of Lake Piaseczno Duze (LPD, Drawa National Park, Poland) covered by a monoculture of Scots pine (*Pinus sylvestris*) and mixed forest with white birch (*Betula pubescens*) as the dominant tree. Experimentally, we also aimed to study the leaching of nutrients from pine and birch litter. Throughout the investigated period runoff waters had low pH, brown colour and high levels of dissolved organic carbon (DOC) – most likely induced by humic acids. Furthermore, considerable levels of nitrogen (N) and phosphorus (P) were found. The highest concentrations of nutrients were observed in runoff collected after heavy rainfall and snow melting. Runoff from the coniferous area contained significantly higher levels of DOC but lower concentrations of N and P compared to runoff collected from the birch-dominated forest. Similar physicochemical conditions were observed in the leaching experiment. Moreover, it was found that the release of chemical substances from both coniferous and deciduous litter was rapid. Our study indicates that surface runoff from forest areas can significantly affect lake chemistry. Based on the simultaneous analyses of littoral water chemistry we suggest that it may contribute to LPD dystrophication through the transportation of high levels of acidic compounds.

Key words: Forest litter / surface runoff / nitrogen / phosphorus / DOC

Introduction

Surface runoff can transport significant loads of nitrogen (N), phosphorus (P) and organic matter from the catchment area to freshwater (Strobel *et al.*, 2001; Vuornenmaa *et al.*, 2002; Astrom *et al.*, 2004). The chemical properties of runoff may vary significantly and depend, inter alia, on catchment area properties such as geomorphology, vegetation and the degree of human impact. In forest ecosystems, the input and output of essential nutrients is relatively small when compared to their total amount of cycling within the system (Hirobe *et al.*, 2004). However, the elements exported from wooded catchments may have a considerable impact on the quality of surface waters (Irfanullah, 2009; Park *et al.*, 2011). In some cases, they can be responsible for dystrophication of lakes resulting from the large quantities of organic matter exported with the surface runoff (Steinberg, 2003). The impact of the surface runoff can also depend on the degree to which the slopes surrounding a lake are inclined – the steeper they are, the greater export of substances may occur. Steep inclination can also lead to the elution of upper layers of soil as well as forest litter directly into the lakes (Sickman *et al.*, 2003). Hongve (1999) has also suggested that plant coverage can affect the physicochemical properties of surface runoff waters.

Climate variations may increase the impact of surface runoff on aquatic environments. In recent decades a decrease in precipitation has been observed in several regions of Poland although a parallel increase in number of heavy rainfall events has been noted (Woś, 1994). Such a phenomenon can lead to saturation of the upper part of soils and a significant increase of flow (Steinberg, 2003). As a result higher levels of chemicals, including nutrients, can be transported from the catchment areas to lakes and rivers.

The following study was undertaken in order to investigate the overland transfer of chemical substances

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from wooded areas and to determine the potential impact of forest litter on the physicochemical properties of the surface runoff waters. We also aimed to study whether the chemistry of surface runoff can trigger the dystrophication of the lake.

Material and methods

Study area

Our studies were conducted within the catchment area of Lake Piaseczno Duże (LPD) located in the eastern part of the Drawa National Park (Northern Poland, Europe) at the latitude and longitude of 53°7'42"N and 16°0'28"E, respectively. It is a non-through flow, stratified, dimictic lake with a surface area of 58.7 ha, shoreline length of 3.75 km, maximum depth of 25.9 m and average of 7.6 m.

The catchment area of LPD covers 154 ha and is 2.6 times larger than the lake's surface. It is almost entirely (98.5%) covered by forests, the remainder being covered by a raised bog. A considerable part of the catchment area (85%) is covered by a monoculture of Scots pine (*Pinus sylvestris* L.), whereas the remaining 15% is covered by mixed forest with white birch (*Betula pubescens* L.) as the dominant tree. Both types of forest are clearly divided from each other. The total length of mixed forest remaining in contact with the shoreline of LPD is 700 m, whereas pine forest borders the shoreline to the length of 3 km.

The catchment area is dominated by medium–high permeable rusty and podzolic soils. The high inclination of slopes (up to 45°) stimulates the erosion of soils and the formation of runoff flow. The morphometric features of the LPD catchment area (steep slope inclinations) indicate a significant contribution of surface runoff to the water balance of LPD. No meteorological or geological data on the water balance of LPD is available; however, based on Bernardt's formula (Czarnecka, 1976) it was calculated that about 25% of the rainwater from the LPD catchment area is transported to the lake as surface or subsurface runoff. The amount of runoff water is comparable with the amount of direct rainfall on the lake. The contribution of the groundwater inflow into the LPD water balance seems to be lower than in lakes situated nearby. During the investigated period the fluctuation of the LPD water level was 50 cm.

The mean chemical composition of rainfall during the investigated period (January 2009–November 2010) was as follows: pH – 6.24, electric conductivity – 21 μSm.cm^{-1}, ammonium (NH_4^+) – 0.81 mg N.L^{-1}, nitrates (NO_3^-) – 0.61 mg N.L^{-1}, total nitrogen (TN) – 2.79 mg N.L^{-1}, organic nitrogen (N_{org}) – 1.37 mg N.L^{-1} and total phosphorus (TP) – 0.11 mg P.L^{-1} (data obtained from the meteorological station located 4.5 km from the sampling sites). Mean precipitation during the investigated period was 52.6 cm (SD $\pm$ 35.3). The maximum precipitation was noted in July 2009 (113 cm).

Field procedures

In order to study the chemistry of surface runoff two characteristic sites were established within the catchment area of LPD. The first (site A) was situated on a slope covered by the Scots pine monoculture and located in the southern part of LPD. The second (site B) was located on a slope overgrown by the mixed forest with white birch as the dominant species and located in the northern part of LPD. Both slopes were directly adjacent to the shoreline and were steep (45°). The similarities of the morphological features of both investigated sites resulted in a comparable formation and strength of surface runoff.

At each site, two separate surface runoff water samplers were installed. Samplers were made of polyvinyl chloride (PVC) gutters (3 m long and 0.15 m wide) and a sealed plastic collector buried at the lower end at an angle that prevented the direct inflow of rainwater. The gutters were placed under the forest litter composed of Scots needles (site A) or high prevalence of birch leaves (site B) and covered with a 0.25 mm mesh. Special care was taken to ensure minimal soil disturbance during the installation of the gutters. Runoff water was collected after each precipitation event and during the melting of the snowpack. Collected samples were then filtered in the field through a cellulose filter GF-C 0.45 μm. Field physical parameters (pH and electric conductivity) were measured using a YSI 556 Multiparameter Instrument. Samples were then transported to the laboratory in a lightproof insulated box containing a cooling factor. Usually the laboratory analyses were conducted immediately after transportation if not, samples were frozen. The following parameters were analysed: NH_4^+ (using the Nessler method), nitrites (NO_2^-, using the sulphanic acid method), NO_3^- (using the sodium salicylate method), N_{org} (using the Kjeldahl method), TP (using the molybdate method after mineralization) and orthophosphates (total reactive phosphorus (TRP), using the molybdate method) (APHA *et al.*, 2005). Dissolved inorganic nitrogen (DIN) was expressed as the sum of each investigated N form. Dissolved organic carbon (DOC) was measured using a SHIMADZU TOC-5000 A analyser. Water colour was determined using the platinum–cobalt colour scale. Daily rainfall data were collected from a meteorological station situated 4.5 km from the study site. Water samples from the pelagic zone were collected during the summer stratification period. Integrated water column samples were collected for each thermal layer. Thermal layer boundaries were determined based on temperature profiles. Littoral water samples were taken approximately 1 m from the shore after heavy rains ($n = 3$). Water transparency was measured using a Secchi disc. Chlorophyll-a was determined after extraction with acetone, chemical oxygen demand (COD) was analysed using the potassium permanganate method, biological oxygen demand (BOD_5) was determined according to the Winkler method, calcium ions were analysed by EDTA titration. These analyses were conducted according to Polish Standards (Hermanowicz *et al.*, 1999). Field physical parameters (pH and electric conductivity), mineral forms of N, N_{org}, TP, TRP and DOC were determined by applying similar methods to those already described for the surface runoff investigations.

Experimental procedures

Forest litter was collected from both sites near the installed surface runoff samplers. One consisted of Scots pine needles, the other of tree leaves (with the prevalence of white birch).

The litter was collected from a surface of 1 m^2 and then dried in a dark room at a temperature of 21 °C. Afterwards 150 g samples of pine and birch litter were placed in separate water tanks and flooded with 20 L of distilled water of known parameters (pH = 6.5, electric conductivity of 2 $\mu Sm.cm^{-1}$, TN of 0.0 mg $N.L^{-1}$, TP of 0.0 mg $P.L^{-1}$ and DOC of 0.0 mg $C.L^{-1}$). Distilled water was used due to the technical difficulties in the collection of large volumes of rainwater from the investigated sites within a short period of time. For 10 days, 500 mL samples of water were collected and subjected to further analyses. Similar physicochemical parameters as in the field experiment were analysed using methods already described. On the first day, samples were collected three times: after 1, 3 and 6 h from the beginning of the experiment. Five replicates of each experiment were conducted.

Statistical calculations

Statistical analyses were determined using Statistica 8.0 (StatSoft, USA). Comparison between samples was assessed using the non-parametric Mann–Whitney *U* test. *P* value < 0.05 was considered as statistically significant.

Results

Field investigations

LPD had initial dystrophic conditions. Its water was characterized by low conductivity, low concentration of calcium ions, pH < 7 in the hypolimnia, (Table 1) and a temporary brown colour of water (up to 52 mg $Pt.L^{-1}$) caused by high concentrations of dissolved organic carbon (up to 36 mg $C.L^{-1}$) and an acid reaction (min. pH 5.2) in the littoral zone.

Collected surface runoff waters were characterized by high concentrations of DOC (from 61 to 162 mg $C.L^{-1}$) and an intense brown colour (average of 224 mg $Pt.L^{-1}$). Low acidity (pH < 6) and moderate conductivity (average 125 $\mu Sm.cm^{-1}$) were also observed. Furthermore, the collected runoff had considerably high concentrations of N and P with a mean of 9 $mg.L^{-1}$ of TN (with a slight prevalence of mineral N) and 0.6 $mg.L^{-1}$ of TP.

The vegetation cover of the catchment area clearly affected the physicochemical properties of the surface runoff waters. Runoff from the area covered by the Scots pine contained twofold higher concentrations of NH_4^+ and N_{org} and almost 30% higher concentrations of DOC as well as a twofold more intense colour of water, lower pH (mean 5.4) and electric conductivity (average by 22 $\mu Sm.cm^{-1}$). In contrast, surface runoff waters collected from the slopes dominated by white birch had significantly higher concentrations of NO_3^- and TP. For most of the analysed parameters, the differences between the investigated sites were statistically significant (Table 2).

The highest concentrations of the investigated chemical compounds in the surface runoff waters and the lowest pH were observed in periods of heavy rainfall and snow melting (Fig. 1). At the same time large volumes of runoff

Table 1. Mean values of physicochemical parameters of water in three thermal layers of LPD during the summer stagnation.

	Epilimnia	Metalimnia	Hypolimnia
Colour (mg $Pt.L^{-1}$)	15	14	14
Transparency (m)	5.7	–	–
pH	7.17	7.04	6.7
Dissolved O_2 (mg $O_2.L^{-1}$)	8.0	9.0	4.6
BOD_5 (mg $O_2.L^{-1}$)	1.5	1.5	2.7
COD_{KMnO_4} (mg $O_2.L^{-1}$)	7.0	6.2	6.6
NH_4^+ (mg $N.L^{-1}$)	0.04	0.02	0.02
NO_2^- (mg $N.L^{-1}$)	n.d.	n.d.	0.002
NO_3^- (mg $N.L^{-1}$)	n.d.	n.d.	n.d.
N_{org} (mg $N.L^{-1}$)	2.4	1.7	1.4
TRP (mg $P.L^{-1}$)	n.d.	n.d.	n.d.
TP (mg $P.L^{-1}$)	0.065	0.065	0.033
El. conductivity ($\mu Sm.cm^{-1}$)	110	110	110
Calcium (mg $Ca.L^{-1}$)	15.0	15.7	16.4
DOC (mg $C.L^{-1}$)	4.6	5.4	8.9
Chloropyll-a ($\mu g.L^{-1}$)	1.60	1.96	1.90
Seston ($g.L^{-1}$)	0.2	n.d.	n.d.

n.d., not detected.

Table 2. Mean values ($\pm$SD, $n = 17$) of physicochemical parameters of surface runoff waters during studied period and statistical significance of the differences between sampling stations.

	Pine	Birch	Mann–Whitney *U* test
Colour (mg $Pt.L^{-1}$)	262.6 ± 96	182 ± 62.8	*
TRP (mg $P.L^{-1}$)	0.4 ± 0.2	0.6 ± 0.3	n.s.
TP (mg $P.L^{-1}$)	0.5 ± 0.3	0.8 ± 0.3	*
N_{org} (mg $N.L^{-1}$)	7.3 ± 3.1	3.1 ± 1.5	***
NH_4^+ (mg $N.L^{-1}$)	5.7 ± 2.0	2.3 ± 1.5	***
NO_3^- (mg $N.L^{-1}$)	0.9 ± 0.3	2.7 ± 1.7	**
NO_2^- (mg $N.L^{-1}$)	0.01 ± 0.009	0.01 ± 0.009	n.s.
DOC (mg $C.L^{-1}$)	96.1 ± 22.5	65.3 ± 9.7	***
El. cond. ($\mu Sm.cm^{-1}$)	114.4 ± 40.4	136.4 ± 33.8	*
pH	5.4	5.8	n.s.

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; n.s., statistically insignificant.

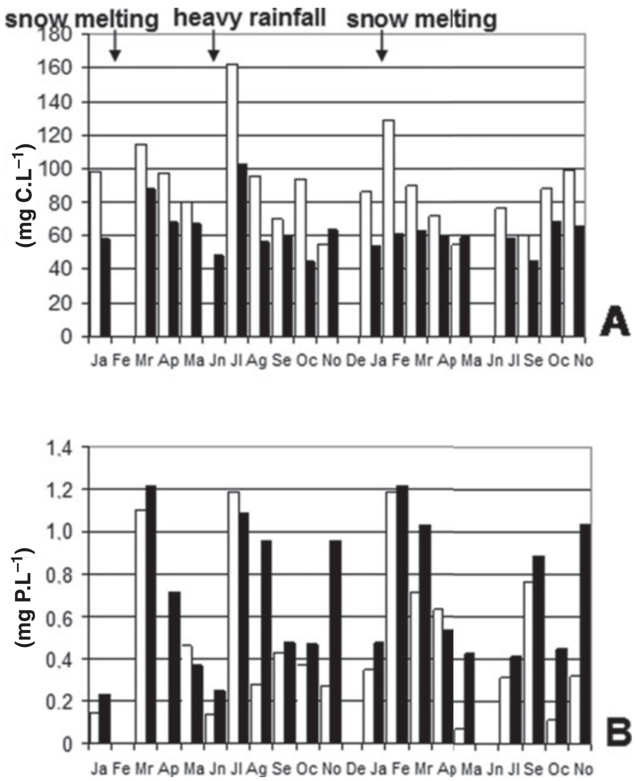

Fig. 1. Monthly variation in DOC (A) and TP (B) concentrations in the surface runoff from the LPD catchment area dominated by the Scots pine (white blocks) or white birch (black blocks). Letters on the *x*-axis corresponds to the consecutive months.

water inflowing to LPD during and after heavy rainfall had a significant impact on the physicochemical properties of water in the littoral zone. During these periods a higher acid reaction (pH 5.2–5.8), more intense brown colour (mean 46 mg Pt.L^{-1}), higher concentration of DOC (mean 26 mg C.L^{-1}) and nutrients (TN 3.8 mg N.L^{-1} and TP 0.1 mg P.L^{-1}) were observed compared to the pelagic water (Table 1). In dry periods the physicochemical properties of littoral water were comparable to the open water.

Laboratory experiment

Results from the experimental investigation demonstrated similar tendencies to those obtained during the field studies. Moreover, it was found that the release of chemical compounds from forest litter to water was rapid (Fig. 2). The greatest decrease of pH as well as the greatest increase in electric conductivity and concentrations of nutrients were observed after the first hour of the experiment. The quantity of chemical compounds leached to the water depended on the studied type of litter. Both coniferous and deciduous forest floors strongly decreased water pH although higher acidity was found in water incubated with pine litter (pH in the range of 3.6–5.9). The acidity of water incubated with birch litter was in the range of pH = 4.3–6.0. Differences in the pH values were statistically significant (Mann–Whitney U test, $P < 0.05$). Significant differences were also observed in electric conductivity (Fig. 2). The conductivity of water incubated with birch litter – mean 40 μSm.cm^{-1} – was approximately twice as high as that of water incubated with pine litter – mean 20 μSm.cm^{-1} (Mann–Whitney U test, $P < 0.001$). N was constantly released from both of the investigated types of litter throughout the experiment as demonstrated by a steady increase in DIN concentration. Slightly higher levels of N were leached from the birch litter and the release rate was also higher than from the pine litter (Fig. 2). NH_4^+ ions prevailed in the DIN, whereas the NO_2^- ions had the least participation. After 6 h of experiment the NH_4^+ ions in the water incubated with birch litter reached a maximum value of 2.0 mg N.L^{-1}. In contrast, only 0.63 mg N.L^{-1} of NH_4^+ was leached from the pine litter after the same period of time. Significantly higher concentrations of TN and TRP were also found in water incubated with birch litter (Mann–Whitney U test, $P < 0.001$). The maximum level of TP leached from the birch litter reached over 1.0 mg P.L^{-1}; whereas in the case of pine litter, the maximum TP concentrations reached only 0.4 mg P.L^{-1}. On the other hand, significantly higher concentrations of DOC were observed in water incubated with pine litter (Fig. 2) and were followed by a higher colour of water (Mann–Whitney U test, $P < 0.01$ for both parameters). The mean colour of water incubated with pine reached 192 mg Pt.L^{-1} while in the case of the birch litter it reached only 125 mg Pt.L^{-1}.

Discussion

Surface runoff has a short-term and episodic character and its chemical properties are therefore difficult to study in the natural environment. However, as indicated by our investigations its potential impact on the chemical properties of the aquatic environment cannot be ignored. In the case of some lakes, including the studied LPD, surface runoff represents an important part of the lake water balance. It can transport large volumes of water into the lake and trigger its chemistry – particularly so in non-through-flow lakes with highly inclined slopes adjacent to the shoreline.

We have found that the forest floor can play an important role in triggering the chemistry of surface runoff and that it can differ depending on vegetation. Collected runoff was characterized by relatively high concentrations of DOC, although a significantly higher level was found within the area covered by Scots pine. Our previous studies have already indicated that coniferous litter has a higher impact on the level of DOC than deciduous litter (Klimaszyk and Rzymski, 2011) whatever the investigated tree species. Our laboratory experiment confirmed the field investigations since a higher concentration of DOC was again leached from the pine litter. This in turn corresponds with Strobel *et al.* (2001) who found a higher participation of DOC in the surface parts of soils overgrown by different coniferous species. Our field investigation revealed,

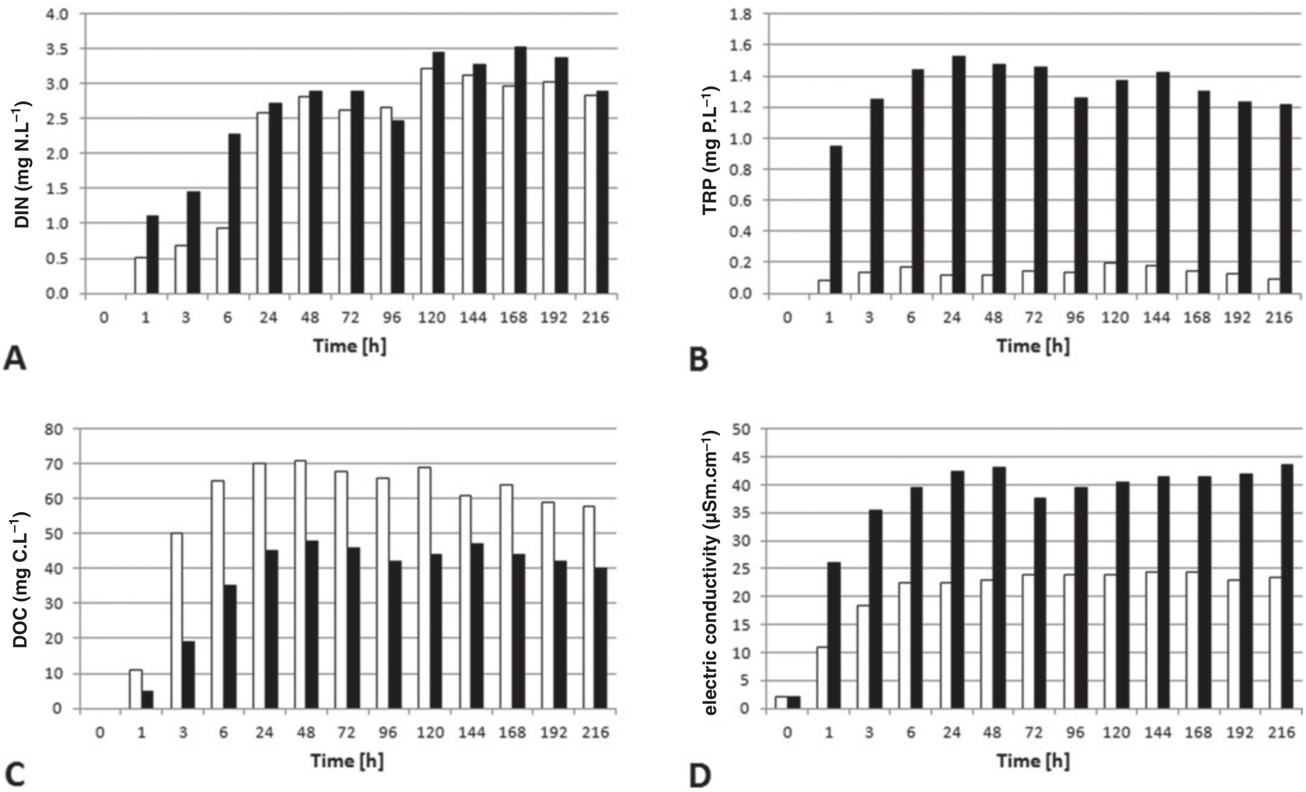

Fig. 2. Changes of DIN (A), TRP (B), DOC (C) and electric conductivity (D) in the water incubated with Scots pine (white blocks) and white birch (black blocks) litter.

however, the seasonal dynamics of DOC in surface runoff. Significant peaks were observed in runoff collected after heavy rainfall and during intensive snowmelt. Such tendencies have been also reported in other studies (Cronan and Aiken, 1985; Hongve, 1999; Klimaszyk, 2006) indicating that the degree of chemical washing-out correlates with the volume of surface runoff. The DOC concentrations found in our study are comparable to its content in waters collected from transitional and raised bogs. Inflows of water characterized by such levels of DOC are considered as one of the main factors contributing to lake dystrophication. The dark colour of many DOC compounds significantly affects the thermal structure and regulates ecosystem production because its absorptive properties impede photosynthesis (Sobek and Tranvik, 2007). High inflows of DOC can also significantly decrease pH – a major allochthonous source of DOC includes humic acids. Therefore, surface runoff can be one of the main factors underlying the first signs of the dystrophication of LPD. We have also found that during periods of heavy rainfall the littoral water was characterized by parallel high concentrations of DOC and an increase in the intensity of water colour. The dystrophication of LPD may, however, proceed at a slower pace than in non-through-flow lakes with considerably lower water volumes and larger wooded catchment areas (Klimaszyk, 2006; Klimaszyk and Rzymski, 2011). Nevertheless, LPD already exhibits several characteristic features of the oligohumic dystrophic reservoir: low electrical conductivity and acid reaction of water in the hypolimnion, low concentrations of calcium and seston, large Secchi depth but at the same time a relatively high concentration of chlorophyll-a. It is therefore suggested that in LPD the chlorophyll is mostly produced by the smallest fraction of algae – picoplankton. In dystrophic lakes energy flows mainly through the community of picoplankton and bacteria, through phagotrophic algae and other elements of the food chain, excluding larger phytoplankton (Hessen, 1992; Jones 1992).

The investigated surface runoff waters were also characterized by a relatively high concentration of N and P exceeding the values observed for most Polish forests and even some agricultural-forest catchment areas. This is probably due to the high inclination of the slopes in the LPD catchment areas particularly near the shoreline. Such geomorphology promotes the formation of surface runoff and increases erosion (Rorke, 2000). It is already known that surface runoff occurs more intensely in mountain catchment areas than in lowland areas (Niemrycz *et al.*, 1993). In our investigation the major factor affecting the concentrations of nutrients in the runoff waters was the intensity of precipitation. An increase in N and P was observed after heavy rainfall and during the melting of the snowpack. Lewis *et al.* (1999) and Sickman *et al.* (2003) have also observed the highest content of biogenic substances in the surface runoff during snow melt. This can be explained by the fact that soil freezing events may increase the rates of N and P loss, with potential effects on their availability followed by the further increase of ecosystem productivity and surface eutrophication (Fitzhugh *et al.*, 2001). Although rainwater (as well as snow) itself can be a source of N and P, the observed concentrations of TP and TN in runoff water were considerably higher than those recorded from on-site precipitation. This in turn indicates a significant role of forest litter in the nutrient enrichment of the surface runoff.

Our results demonstrate that the concentration of N and P dependent on the type of forest. Runoff on slopes covered by birch was characterized by significantly higher concentrations of nutrients. The lower concentrations found in runoff collected from pine forest can be associated with a smaller pool of these elements in the coniferous detritus. Furthermore, it has been suggested that N and P are largely withdrawn from the needles before they are shed (Wilpiszewska, 1990; Pensa *et al.*, 2007). Deciduous trees can also withdraw some N and P content during leaf senescence but the magnitude of this process may significantly differ depending on the nutrient availability in soils and tree species (Schulze *et al.*, 2009). Interestingly we noted that runoff collected from the slopes overgrown by Scots pine was considerably richer in NH_4^+ ions. Zieliński *et al.* (1999) have also experimentally demonstrated that water incubated with coniferous litter is characterized by significant concentrations of this N form. At the same time our study indicated that pine litter significantly decreased the pH of water (minimal observed pH in the field investigations was 4.1, in the experimental studies – 3.7). It has already been shown that the activity of nitrifying bacteria can be strongly inhibited under acidic conditions (Grunditz and Dalhammar, 2001). Thus, we suggest that it is rather the specific physicochemical conditions that underlay the reason for the higher level of NH_4^+ found in surface runoff occurring within the coniferous forest rather than the large quantity of N in the pine litter. This hypothesis is also supported by our experimental procedure in which significantly larger concentrations of NH_4^+ were found in water incubated with birch litter.

Our study indicated that forest litter can be a source of considerable loads of N, P and carbon supplying the lake through surface runoff. Furthermore, deposition of forest detritus directly into the littoral zone can enrich its water in nutrients and other chemical compounds. Our study demonstrated that the leaching of chemical substances from both, coniferous and deciduous litter occurs rapidly. This in turn highlights the role of surface runoff in the elution and transport of chemicals. Our finding is contradictory to some other studies in which a relatively slow release of nutrients from plant detritus has been observed (Hongve, 1999; Hirobe *et al.*, 2004). However, the cited studies involved only fresh plant detritus which releases N, P and other elements slowly during its gradual decomposition. In natural forest environments chemical compounds are derived not only from the recent litter but also from the older organic matter in the lower forest floor horizons (Park and Matzner, 2003).

Scots pine monocultures are very common types of forests in Central Europe. Among many other potential effects of Scots pine monoculture on the environment, we have indicated here that it can contribute to the humification and acidification of lakes, particularly when it largely overgrows an area near the shoreline.

Conclusions

Our study demonstrated that surface runoff can supply lakes with large loads of nutrients and organic matter. In forests the chemistry of the surface runoff can be affected by the vegetation type. Higher loads of N and P can be transported from deciduous forests. In contrast, coniferous litter can be a significant source of DOC. This in turn can lead to the dystrophication of lakes, particularly non-through-flow lakes with a high contribution of surface runoff in their water balance, situated in hilly catchment areas overgrown by monocultures of coniferous tree species.

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References

APHA, AWWA, WEF, 2005. Standard Methods for the Examination of Water and Wastewater, 21st edn, APHA, AWWA, WEF, Washington, DC.

Astrom M., Aaltonen E.K. and Koivusaari J., 2004. Changes in leaching patterns of nitrogen and phosphorus after artificial drainage of a boreal forest – a paired catchment study in Lappajarvi, Western Finland. *Boreal Env. Res.*, *10*, 67–78.

Cronan C.S. and Aiken G.R., 1985. Chemistry and transport of soluble humic substances in forested watersheds of Adirondack Park, New York. *Geochim. Cosmochim. Acta*, *49*, 1697–1705.

Czarnecka H., 1976. Attempt to outflow calculations in small uncontrolled drainage basins on the basis of the soil cover. *Gosp. Wod.*, *8–9*, 225–230 (in Polish).

Fitzhugh R.D., Driscoll C.T., Groffman P.M., Tierney G.L., Fahey T.J. and Hardy J.P., 2001. Effects of soil freezing disturbance on soil solution nitrogen, phosphorus, and carbon chemistry in a northern hardwood ecosystem. *Biogeochemistry*, *56*, 215–238.

Grunditz C. and Dalhammar G., 2001. Development of nitrification inhibition assays using pure cultures of Nitrosomonas and Nitrobacter. *Water Res.*, *35*, 443–440.

Hermanowicz W., Dojlido J., Dożańska W., Koziorowski B. and Zerbe J., 1999. The Physical-Chemical Analyses of Water and Wastewater. Arkady Press, Warsaw.

Hessen D.O., 1992. Dissolved organic carbon in a humic lake: effects on bacterial production and respiration. *Hydrobiologia*, *229*, 115–123.

Hirobe M., Sabang J., Bhatta B.K. and Takeda H., 2004. Leaf-litter decomposition of 15 tree species in a lowland tropical rain forest in Sarawak: dynamics of carbon, nutrients, and organic constituents. *J. Forest Res.*, *9*, 347–354.

Hongve D., 1999. Production of dissolved organic carbon in forested catchments. *J. Hydrol.*, *224*, 91–99.

Irfanullah H.M., 2009. On the role of forested catchment in acid lake limnology. *Turk. J. Fish. Aquatic Sci.*, *9*, 227–230.

Jones R.I., 1992. The influence of humic substances on lacustrine planktonic food chains. *Hydrobiologia*, *229*, 73–91.

Klimaszyk P., 2006. Peatbog – humic water complex in forest landscape: factors determining its functioning. *Pol. J. Environ. Stud.*, *15*, 384–388.

Klimaszyk P. and Rzymski P., 2011. Surface runoff as a factor determining trophic state of midforest lake (Piaseczno Małe, North Poland). *Pol. J. Environ. Stud.*, *5*, 1203–1210.

Lewis W.M., Melack J.M., Mcdowell W.H., Mcclain M. and Richney J.E., 1999. Nitrogen yields from undisturbed watersheds in the America. *Biogeochemistry*, *46*, 149–162.

Niemrycz E., Taylor R. and Makowski Z., 1993. Endangere of Fresh Waters, Biblioteka Monitoringu Środowiska, Warsaw.

Park J. and Matzner E., 2003. Controls on the release of dissolved organic carbon and nitrogen from a deciduous forest floor investigated by manipulations of aboveground litter inputs and water flux. *Biogeochemistry*, *66*, 265–286.

Park S-R., Lee H-J., Lee S-W., Hwang S-J., Byeon M-S., Joo G-J., Jeong K-S., Kong D-S. and Kim M-C., 2011. Relationships between land use and multi-dimensional characteristics of streams and rivers at two different scales. *Int. J. Limnol.*, *47*, 107–116.

Pensa M., Jalkanen R. and Liblik V., 2007. Variation in Scots pine needle longevity and nutrient conservation in different habitats and latitudes. *Can. J. Forest Res.*, *37*, 1599–1604.

Rorke B.B., 2000. Soil erodibility and processes of water erosion on hillslope. *Geomorphology*, *32*, 385–415.

Schulze I.-M., Bolte A., Schmidt W. and Eichhorn J., 2009. Phytomass, litter and net primary production of herbaceous layer. *In*: Brumme R. and Khanna P.K. (eds.), Functioning and Management of European Beech Ecosystems, Springer-Verlag, Berlin, 155–181.

Sickman J.O., Leydecker A., Chang C.C.Y., Kendall C., Melack J.M., Lucero D.M. and Schimel J., 2003. Mechanisms underlying export of N from high-elevation catchments during seasonal transitions. *Biogeochemistry*, *64*, 1–24.

Sobek S. and Tranvik L.J., 2007. Patterns and regulation of dissolved organic carbon: an analysis of 7,500 widely distributed lakes. *Limnol. Oceanogr.*, *52*, 1208–1219.

Steinberg C.E.W., 2003. Ecology of Humic Substances in Freshwaters, Springer, Berlin.

Strobel B.W., Hansen H.C.B., Borggaard O.K., Andersen M.K. and Raulund-Rasmussen K., 2001. Composition and reactivity of DOC in forest floor soil solutions in relation to tree species and soil type. *Biogeochemistry*, *56*, 1–26.

Vuornenmaa J., Rekolainen S., Lepisto A., Kenttamies K. and Kaupilla P., 2002. Losses of nitrogen and phosphorus from agricultural and forest areas in Finland during the 1980s and 1990s. *Environ. Monit. Assess.*, *76*, 213–248.

Wilpiszewska I., 1990. Productivity and chemical valorization of mire vegetation in postglacial agriculutral landscape. *Ekologia Polska*, *38*, 3–72.

Woś A., 1994. The Wielkopolska Lowland Climate, Wydawnictwo Naukowe UAM, Poznań.

Zieliński P., Górniak A. and Choroszewska K., 1999. Changes in water quality induced by the decomposition of plant detritus. *Acta Hydrobiol.*, *41*, 119–126.