POLISH JOURNAL OF ECOLOGY (Pol. J. Ecol.)	48	2	103–161	2000

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BIOGEOCHEMICAL FUNCTIONING OF HYDROLOGICALLY MODIFIED PEATLANDS AND ITS EFFECT IN EUTROPHICATION OF FRESHWATERS

I dedicate this work to my wife, Hanna

ABSTRACT: It has been found that, except for trace metals (Zn, Cu, Pb and Cd), peatlands having been hydrologically modified as a result of various anthropogenic activities do not play a barrier role for mineral elements incoming from the catchments and the atmosphere. In contrast, they may be a source of P compounds that additionally supply aquatic ecosystems. With use of multiple regression it has been revealed that eutrophication of peatlands and stream waters is favoured primarily by influx of biogenic elements from the catchments, dynamics of water storage by the peatland, amount and pH of precipitation, as well as by influence of numerous modifying ions. On a landscape scale, hydrologic changes of forest watersheds with peatlands, as well as deforestation and reduction of acreage of peat meadows in relation to arable lands are reasons of biogeochemical transformations of the lakeland landscape. Overall, these factors increase matter transfer from terrestrial to aquatic ecosystems.

KEY WORDS: peatland, biogeochemistry, eutrophication, humic lake, transitional peatland, drainage

1.INTRODUCTION

Mire systems, including natural peatlands, play specific transitional role between terrestrial and aquatic ecosystems (Moore and Bellamy 1974, Clymo 1983). Characteristic feature of mires and, at the same time, the most important habitat condition that determines functioning of the biocenoses is their continuous or periodical flooding or existence of a shallow surface water body (Kulczyński 1939/40, Horne and Goldman 1994). Thus, they are particularly susceptible to man-induced changes in hydrologic conditions. Human activities associated with various economical needs have led to transformation of entire biocenosis and loss of wetland function (Maltby et al. 1996). According to Churski (1993), about a third of wetland area in Europe has been lost in last decades.

In the present landscape of temperate climatic zone being dominated by agriculture and forestry, a considerable part of natural peatlands have undergone more or less radical transformations (Clymo 1983). Usually, these processes result from changes in hydrologic conditions. As an effect, we deal with a numerous and variable group of natural systems that can generally be qualified as hydrologically modified peatlands (Mitsch and Gosselink 1993). These include not only peatlands which had been drained and then managed as productive meadows and pastures, but also mires where water outflow had been regulated in order to adjust water level in lakes for fishery purposes, to supply water to mills or power plants (Kondracki 1972), as well as peatlands drained for forest melioration purposes (Heikurainen et al 1978, Lundin and Bergquist 1990, Richardson and McCarthy 1994), for peat extraction, hydrologically modified mire relics in drained agricultural areas, and others. It can generally be assumed that, regardless of the extent of site modifications and transformations of the biocenosis, a feature that makes such systems distinct from the natural mires is that water flow has been liberated, and hence accelerated.

These are the peatlands that have been the object of this study. Hydrologic modifications, the objects were exposed to, included liberation of water flow due to establishment of a water course, although it did not provide effective drainage, as well as, effective drainage of the peatland with subsequent use of its area as meadows, i.e. agricultural melioration.

A pattern of nutrient cycling that systematises ecosystem picture (Krebs 1997) is of vital importance in the case of ecotones. Mire systems are qualified as ecotones (Horne and Goldman 1994), because they are often considered as being a link between land and water ekosystems. Their biogeochemical role as a sinks, sources or a transformers of chemical components (Mitsch and Gosselink 1993) has become important for understanding of such global processes as eutrophication (Morris 1991, Jansson et al. 1994, Hillbricht-Ilkowska 1995), acidification (Gorham et al. 1984, Gorham 1987, Lamers et al. 1997) and transport of toxic metals (Gilmour and Gale 1988). Moreover, there is a growing concern about the peatlands' role in global warming (Gorham 1991, Wieder and Yavitt 1994, Thormann et al. 1998). To present the role of hydrologically modified peatlands in matter cycling through the landscape is one of the main objectives of this work.

Matter retention in peatlands and interception of mineral components from water flux (from the catchment and the atmosphere) is associated with functioning of main trophic types of the peatlands, namely: 1. rheophilous or minerotrophic, i.e. fens and swamps, 2. ombrophilous or ombrotrophic, i.e. bogs and 3. transitional mires (Kulczyński 1939/1940, Moore and Bellamy 1974, Mitsch and Gosselink 1993). The main feature that makes the peatland types distinct from each other is a relation between water inputs carrying elements from the catchment area and the atmosphere. Hydrology of fertile minerotrophic mires is dominated upon a balance: inflow from the catchment minus outflow, whereas that of poor ombrotrophic peatlands: atmospheric precipitation minus evapotranspiration (Ivanov 1957, Ingram 1983).

In the literature, an opinion prevails of considerable ability of mires to exclude nitrogen, NO_3-N in particular, from the water throughflow. This applies to both fertile fens (Kitchens et al. 1975, Lee et al. 1975, Tilton and Kadlec 1979, Nichols 1983, Brinson et al. 1984, Peterjohn and Corell 1984, Kruk 1997a) and ombrotrophic bogs (Hemond 1980, Verry and Timmons 1982). With regard to phosphorus, the picture is less clear. Mires with throughflowing streams have not been found to retain total phosphorus (Devito et al. 1989, Stachurski and Zimka 1994), and factors that determine periodical losses of phosphorus include cyclic flooding (Bayley et al. 1985, Richardson and Marshall 1986), P conversion into organic forms (Kemp and Day 1984, Elder 1985), and possible displacement by sulphate ions (Kruk 1996). Authors generally agree that ombrophilous peatlands have conspicuous abilities of retaining SO_4-S (Hemond 1980, Bayley et al. 1986, Urban et al. 1989), metals (Verry and Timmons 1982, Kruk 1990, Urban et al. 1995), including trace metals (Coupal and Lalancette 1976, Hemond 1980). At the same time, there is strong evidence that these elements are not retained within peatlands of fen type (Brinson et al. 1984, Kruk 1990, Stachurski and Zimka 1994). Importance of hydrologic factors for mire ability to retain elements should be emphasised.

On this background, influence of hydrologic modifications on intrasystem element cycling in peatlands seems to be of crucial importance. In this work, disturbances in hydrologic conditions, which principally consist in making a peatland more open to water flow, relate to modified natural mire systems. The systems studied are originated from initial and advanced successional stages of transitional peatlands showing natural, though deformed due to the hydrologic modifications, a tendency to ombrotrophy. Anthropogenic transformations have coincided here with natural succession of the peatlands. In the natural succession pathway, a peatland system with humic lake surrounded by a peat moss (*Sphagnum* sp.) mat comes first to a peatland with bog (Weber 1908, Stangenberg 1936, Marek 1982, Kratz and De Witt 1986). This natural tendency has been disturbed to such an extent that the dominant biogeochemical process in the examined systems manifested by changes in plant cover is eutrophication (Kruk 1997b, c). Also relic humic lakes within peatlands lose their typical acidic character and submit specific trophic transformations (Górniak 1996). It should be marked, that the name "humic lakes" for such a water bodies is remained in the study for simplification. Common origin of the peatlands studied is confirmed by occurrence of gyttia in each of the object examined. Furthermore, the peat deposits are mainly formed by sedge-moss peat typical of transitional peatlands. In the area of the Masurian Lakeland, this represents a successional stage common to development history of the peatlands (Olkowski 1972, Kloss 1993).

The main objectives of this study were following:

1. to synthesise patterns of retention and losses of mineral components within five peatland systems which had been hydrologically modified; based primarily on detailed authors's results (Kruk 1997b, c, d, e),

2. to find out factors responsible for eutrophication of bog peatlands through seasonal analysis of hydrochemical and hydrologic conditions that affect retention of major nutrient elements in a peatland with transitional bog eutrophied by a water course,

3. to recognise factors responsible for losses of essential elements favouring water eutrophication (N and P) from hydrologically modified peatlands

4. to outline synthetically tendencies for lakeland watersheds to modify element cycling as an effect of changes in land use, such as deforestation or peatland melioration.

This work aimed at contributing to knowledge of biogeochemistry of hydrologically modified peatlands. Mechanisms of elemental fluxes through such complex natural systems as peatlands have not been fully recognised yet (Urban et al. 1995). The role of anthropogenic transformations in these environments in relation to other landscape components, including lakes, has not been determined, either (Krug 1993). Is it reasonable to attribute large scale drainage and channelling that have been performed since the turn of 19th and 20th century in order to regulate connections among Masurian lakes (Mikulski 1966) to accelerated lake eutrophication? To what extent have the activities overlapped with biogeochemical effects of the watershed deforestation, the latter one being decisive for lake water quality (Nilsson and Haakanson 1992)? Recognition of biogeochemical effects of human economic activities in the landscape, among which modifications of natural hydrologic conditions of ecosystems belong to the most radical ones, should be helpful in taking proper economic decisions and planning.

2. STUDY AREA

The studies on transport of mineral components through hydrologically modified peatlands were conducted in a region of the Masurian Lakeland (Kondracki 1988), in the northern part of Puszcza Piska primeval forest and in an agricultural area near Jorzec lake situated northwards of Mikołajki (Fig. 1). Geographic co-ordinates of the area are 21° 30' E and 53° 50' N, and the altitude of its lowest point is 118 m a.s.l. Main part of the studies on elemental fluxes was performed in five peatland systems, two of which included peatlands with relic humic lakes, the next one was a peatland with transitional bog, and the last two were drained peatlands with meadows, first of them surrounded with a forest, while the second one adjacent to arable fields. All the peatlands are of limnogenous origin, this being documented by the occurrence of coming up to 8–9 m thick carbonate gyttia deposits (Dokumentacje torfowisk 1966). Hydrologic modifications of the systems consisted in: 1. liberation of water throughflow by connect-

Fig. 1. A scheme of the study area. A–E – examined peatlands (see Table 1 for characteristics), 1–5 catchments in forested landscape, 6–9 – catchments in agricultural landscape, a – peatland areas, b – watershed boundaries, c – northern edge of Piska primeval forest, d – sampling stations for stream waters and subsurface waters, e – stations for precipitation sampling.

ing two lakes with a watercourse (the peatland with Żabie lake and the peatland with transitional bog); 2. liberation of water flow by draining a large area of meadows with a ditch (connecting the peatland with Pietrzysko Lake); 3. drainage of peatland followed by its transformation into a meadow; the draining ditches comprise effluxes of subsurface waters rising in the edge zone of peatland area (both peatlands with meadows). General characteristics of the examined objects are given in Table 1.

It should be emphasised that the peatlands under study differed markedly with regard to vegetation cover. In most cases, the vegetation was in the phase of rapid transformations. Therefore, its characteristics were often confined to a list of dominant species or even higher syntaxonomic groups. The peatlands with humic lakes are overgrown with plant communities resembling to certain extent those typical of the period preceding the hydrologic modifications. These include, for instance, relics of a peat moss (*Sphagnum* sp.) mat in the riparian zone of the lakes. On the mat, however, common reed *Phragmites australis* Trin. with scented fern *Dryopteris thelypteris* (L.) A. Gray predominates instead of sedge communities. Additionally, degraded spruce forest on peat *Sphagno girgensohnii-Piceetum* Polak. 1962 with constantly increasing dominance of birch *Betula pubescens* Ehrh. can be found at this site. Within the peatlands, in the zone of water outflow in particular, fertile alder-carr communities *Carici elongate-Alnetum* Koch 1926 have been formed (Table 1, Kruk 1997b).

A diverse mosaic of plant communities is also characteristic of the peatland with transitional bog. Its central part is covered with well-developed sedge communities typical of transitional peatlands: *Caricetum rostratae* Rübel 1912 and *Caricetum limosae* Br.-Bl. 1921. In the western, less modified part of the peatland, fragmented community of bog *Sphagnetum magellanici* Kast. et Flösn. 1933 occurs and a zone covered with a well-developed bog coniferous forest *Vaccinio uliginosi-Pinetum* Kleist 1929. Then, along the watercourse, the peat moss (*Sphagnum* sp.) mat is overgrown with a more fertile community with common reed *Phragmites australis* and scented fern *Dryopteris thelypteris*. A large area is covered with a degraded bog coniferous forest (Table 1, Kruk 1997c).

The drained peatlands are not so phytosociologically diverse. They are mainly covered with semi-natural fertile sod meadow communities of the class *Molinio-Arhenatheretea* R. Tx. 1937 (Table 1). The mid-forest meadow was not fertilised nor mowed in the years of the study, and the green crop adjacent to arable fields was treated with ca. 25 kg of N (as ammonium nitrate) ha^{-1} yr^{-1} in 1992–1994 only. Fertilisation, mowing and pasture use of the meadow was extensive and confined to about 20% of its area.

Water pH of the examined peatlands varied in a narrow range, the pH values having oscillated around 7, except for waters of the transitional bog (pH = 5.3) maintaining some features of ombrotrophy (Table 1).

In order to characterise fluxes of mineral components through various lakeland watersheds, both forested and deforested ones, additional studies were carried out in a few partially peaty catchments in the northern part of the Puszcza Piska primeval forest and its agricultural surroundings (Fig. 1). The forested watersheds can be ranked in an order of increasing degree of disturbances in hydrologic systems of their peatland areas. The watersheds in the agricultural landscape can be ranked accordingly from the greatest to the smallest percentage cover of drained meadow areas. These ranks show in a simplified way courses of anthropogenic pressure in the present-day lakeland landscape.

The following objects were chosen for the studies in the silvicultural landscape (Fig. 1):

Table 1. General characteristics of the examined peatlands. Data from Dokumentacja torfowisk (1966) and author's own measurements.

Characteristic	Site				
	Peatland with eutrophied humic lake (Pietrzysko lake)	Peatland with eutrophied peatland lake (Żabie lake)	Peatland with eutrophied transitional bog	Drained peatland with meadow in forest landscape	Drained peatland with meadow in agricultural landscape
Area (ha)	6.7	1.6	60.5	16.7	38.1
Main plant communities	Community with downy birch, alder carrs, remains of bog coniferous forest	Alder carrs, community of common reed and scented fern	Bog with *Caricetum lasiocarpae*, *C .rostratae*, community of common reed and scented fern, fragments of bog coniferous forest	Communities of non-moved meadows from the class of Molinio-Arrhenatherea with high contribution of stinging nettle	Communities of moved meadows from the class of Molinio-Arrhenatherea. Patches of alder carr and willow brushwood
Hydrography	Pietrzysko lake (1.3 ha); inflow and outflow with ditches (Krutynia river catchment)	Żabie lake (0.6 ha); inflow and outflow with Lisunka stream (Krutynia river catchment)	In the central part a hag peat with subsurface water body, a watercours flowing through the peatland (Krutynia river catchment)	Periodically wet meadow with a ditch discharging waters to Krutynia river	Periodically wet meadow with outflow with ditch and system of drains (Jorka river catchment)
Land use and vegetation in catchment areas	Dominance of forested areas with meadows instead of mires. In the lateral catchment – mixed decidous forest	Dominance of forested areas and meadows instead mires	The channel flowing through the peatland rises in Majcz Wielki lake and flows through drained mires. In the thin belt of lateral catchment – mixed coniferous forest	Fresh and mixed coniferous forests and enclaves of alder carr and bog coniferous forest usually drained by ditches	Arable fields mostly with cereals and rape.
Peat type, degree of decay and mean deph (m)	Sedge-moss peat, low degree of decay (1.2)	Moss and alder peat, low degree of decay (1.5)	Raised Sphagnum peat and sedge-moss peat, low degree of decay (1.9)	Sedge-moss peat, alder peat, moderate degree of decay (1.5)	Sedge-moss, sedge and rush peat, high degree of decay (1.4)
pH of peatland (lake) waters	7.5	8.0	5.3	7.2	6.9

1. A small catchment of a slope-foot spring was assumed to be least disturbed. It is located near Gardyńskie lake and comprises 2.8 ha of an oak-hornbeam forest and a small fragment of alder forest covering about 10% of the area.

2. A system with slightly modified hydrology was a forested catchment with 186 ha of a mixed coniferous forest drained by a water course flowing through a 13 ha mire overgrown with alder and birch stands. The area constitutes a sub-catchment of the next (3.) system.

3. A whole forest-mire-meadow catchment of 219 ha situated near Skok lake. The terminal section of the watercourse drains a 14 ha mid-forest meadow.

4. A forest-meadow watershed of an area of 173.5 ha. The meadow occupies 12% of the catchment area, and additionally drained bog coniferous forests occur here (3% of the area).

5. A catchment covering 17.5 ha of complex management: there is 1.3 ha of a moist mid-forest meadow with a ditch, 1.5 ha of a bog coniferous forest drained with the ditch, whereas the remaining area is covered with mixed and fresh coniferous forests on mineral soils.

Additionally, four watersheds in the agricultural landscape were included into the studies, all of them were situated in the surroundings of Faszcze and Baranowo villages (Fig. 1):

1. A catchment used predominantly as a meadow (80% of the area) was a small (7.1 ha) drainage sub-catchment of a larger system of a drained peatland.

2. A field-meadow catchment of an area of 140.5 ha with a drained peatland and a meadow covering 27% of the entire area.

3. An agricultural field-meadow watershed covering 228 ha located between Faszcze and Baranowo villages, with meadows occupying 10% of the area.

4. A watershed managed almost completely as crop fields. It is a drainage catchment that feeds a drained peatland with meadow. The catchment covers 24.7 ha, and the meadow constitutes only 4% of the area. It has been used for cultivation of mixed cereal crops and fertilised with ammonium nitrate at the rate of approximately 50 kg of N ha^{-1} yr^{-1} during the study period.

3. METHODS

3.1. GENERAL ASSUMPTIONS

These studies were carried out in the years 1992–1996, in two study periods: February 1992 – January 1994 and October 1994 – October 1996. Hydrologic studies and water sampling took place once a month. The peatlands with humic lakes were examined during the first (Żabie lake) and second (Pietrzysko lake) period. The peatlands with transitional bog and with meadow in the agricultural area were investigated during the two periods over 4 years, whereas the peatland with a mid-forest meadow – over 2 years, in 1994–1996 (Fig. 1). Most catchments representing changes in land use were studied in the years 1994 – 1996, only the forest-mire catchment and its extension, i.e. the forest-mire-meadow catchment, were investigated in the former period, catchments 2 and 3 on Fig. 1 respectively.

A principal methodological assumption of studies on transport of elements through peatlands and catchments is adaptation of inflow-outflow approach applied to biogeochemical studies in forest watersheds (Bormann and Likens 1993). Elemental fluxes through a catchment can thus be described on the basis of the difference between atmospheric input and streamwater runoff. Precisely such a pattern was applied to analyse element retention in and losses from the whole catchments characterised by different percentage of peatlands (Chapter 4.6). Because the hydrologically modified peatlands examined were transition systems receiving matter from adjacent ecosystems, modification of the pattern was necessary. This consisted in adding inflows from the catchment of peatland to the inflow – outflow model mentioned above (Fig. 2). Such an approach assumes that a watercourse flowing through a given system is a part of the system and as such it should be balanced together with the peatland ecosystem. The applied "inflow – outflow" approach is a part of more comprehensive studies on budgets of mineral compounds, wherein all ecosystem fluxes and pools are being considered (Johnston 1991).

The above method fits well to hydrography of the peatlands examined. Because the systems include lakes or at least have been

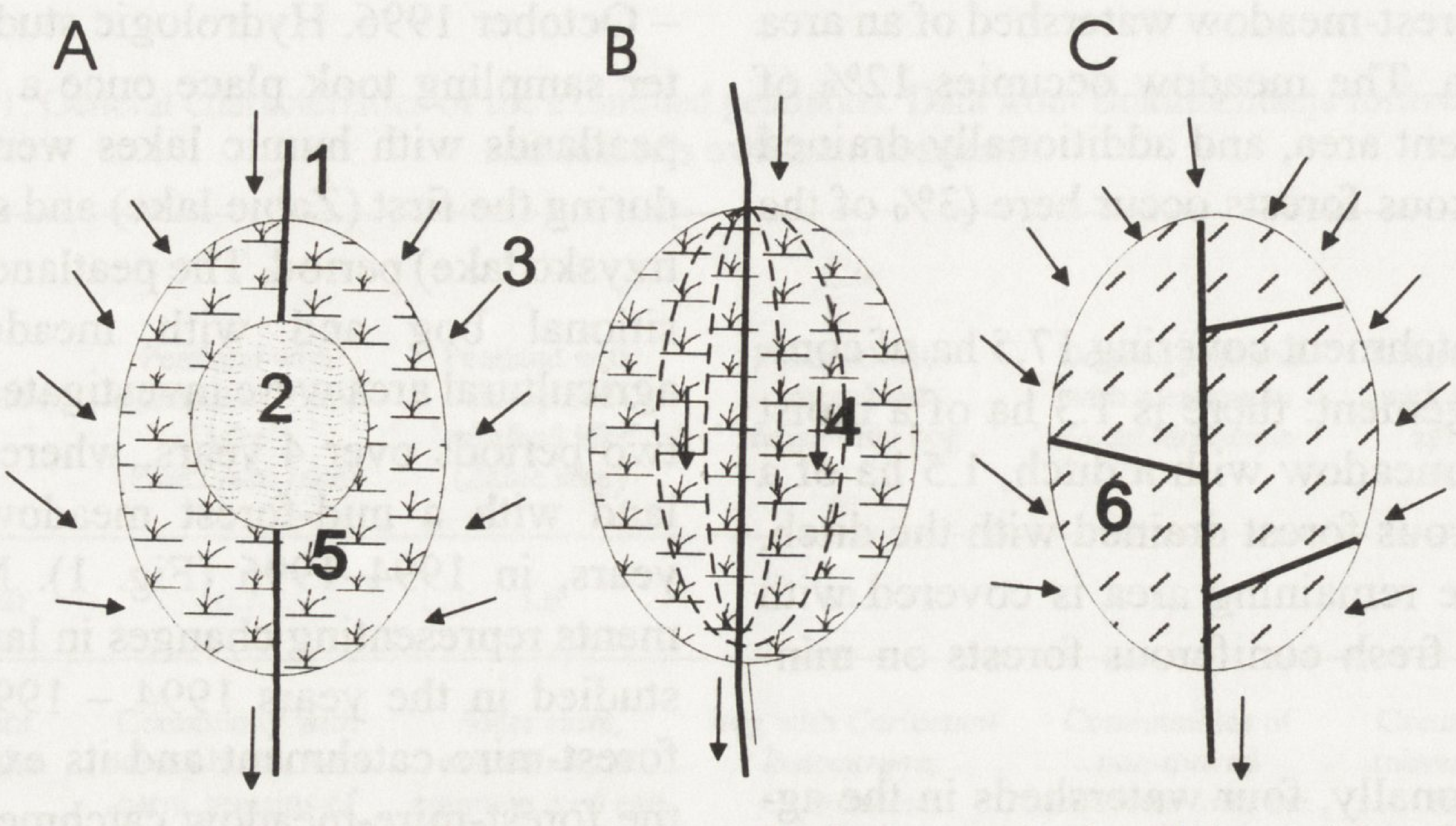

Fig. 2. A scheme of water flow through the examined peatlands. A – peatlands with humic lakes, B – peatlands with transitional bog, C – drained peatlands. 1 – streams and drains, 2 – small humic lakes, 3 – directions of subsurface water flows into peatlands, 4 – directions of water flows through peatlands with transitional bog, 5 – mire, 6 – meadow.

formed from lakes, flow of water and chemical substances is analogous to lakes with catchment inflows and outflows (Fig. 2). Therefore, a basic equation of water budget adopted in this work is the following formula that determines water fluxes in such lakes (Mikulski 1970, Choiński 1995):

$$(P_j + H_d) - (E_j + H_w) = \Delta R,$$

where: P_j – atmospheric precipitation,

H_d – surface and subsurface inflow from the catchment area,

E_j – evapotranspiration,

H_w – surface and subsurface runoff from the lake,

ΔR – a difference in water storage in the lake between the beginning and the end of the budget year.

The above formula was converted into the following form:

$$(P_j + H_d) - H_w = E_j + \Delta R$$

where H_w represents surface runoff, while evapotranspiration E_j and changes in water storage ΔR were put together, as being not measured.

According to the above assumptions, retention (+) or losses (–), i.e. negative retention, of particular forms of elements (RL_x) were calculated as differences between inflow and outflow totals loads using a general balance formula:

$$RL_x = (Ia_x + Iw_x) - Ow_x,$$

Where: Ia – atmospheric input,

Iw – inflow from the catchment area,

Ow – streamflow output.

Inputs and outputs loads were calculated as a product of element concentration and flow rate multiplication. Inflow from the catchment included inflows with stream and ditch waters, as well as subsurface inflows. Subsurface element loadings were figured out from the element concentrations and hydrologic measurements in the following components of water flow: outflow in slope-foot spring (the peatlands with humic lakes) (Kruk 1997b), subsurface waters of the catchment (the peatland with a mid-forest meadow) (Kruk 1997d) and drain outflow (the peatland with a mid-field meadow) (Kruk 1997e). In the case of peatland with a transitional bog, an influence of the most adjacent catchment was neglected due to its small area in relation to the peatland size (Kruk 1997c).

The assumed calculation method is not free from numerous simplifications. Most of all, retention includes also conversion of an element into gaseous forms (denitrification, release of ammonia and hydrogen sulphide), as well as conversion of dissolved forms of a given element (e.g. NH_4 into NO_3, inorganic N and P into their organic forms). To simplify, additional supply of elements with fertilisers (estimated application rates were known) and losses of the elements from the meadows due to harvesting (values not measured) were not included into the calculations, though they were taken into account to interpret the results.

Main parameters used for description of mineral component fluxes through the peatlands and watersheds included: 1. hydrologic parameters, such as precipitation sums, water inflow from the catchment, outflow from the peatlands and finally evapotranspiration coupled with changes in water discharge, 2. elemental concentrations in the waters and 3. yearly and monthly loads incoming from the atmosphere and the catchment and those lost in outflowing waters expressed per unit area of a peatland.

3.2. METHODS OF SAMPLE COLLECTION AND CHEMICAL ANALYSES

Atmospheric precipitation in 1992 – 1994 was measured at the Hydrobiological Station of PASc, some 4–5 km far from the examined peatlands, whereas in 1994 – 1996 – near Majcz Wielki lake, 0.5–2 km far from the mid-forest peatlands. In those years, an additional station was established about 1 km far from the watershed with a meadow to record precipitation in the agricultural area (Fig. 1).

The hydrologic studies aimed at determining precipitation sums and volumes of water inflow to and outflow from the peatlands. Precipitation sums were recalculated from water volume entering a funnel of a known diameter and then collected by a container. To measure flow volumes in watercourses, use was made of existing culvert pipes of known cross-sections. Submersible floats were used for measurements of velocity of water flow. The latter measurements were made in 3–5 replications.

Samples of running waters for chemical analyses were taken to a polyethylene collector. Water samples from drains and slope-foot spring were collected directly at their outlets, whereas subsurface water was sampled from a piezometer established at the foothill of the catchment of peatland with a mid-forest meadow. The samples were taken when the piezometer refilled with water after pumping out water that had flown in between successive sampling dates (Kruk 1990).

Bulk precipitation was monitored by two shaded polyethylene collectors at each station. The collectors were fitted with funnels and sheltered by a polyethylene net of 0.1 mm mesh size. One collector was additionally equipped with a mineral filter (Whatman GF/F 0.7 mm) and contained a spoon of salicilic acid to prevent development of microflora and ammonia volatilisation (Stachurski and Zimka 1984). The second collector had neither such filter nor acid. Samples taken from the first collector were used for analyses of dissolved nitrogen and phosphorus forms and sulphate, whereas those from the second one – for evaluation of particulate nitrogen and phosphorus contents and concentrations of metals and trace elements.

Immediately after sampling, water collected from the watercourses, drains and the slope-foot spring was filtered through a polyethylene net of 0.1 mm mesh size and designed for analyses of particulate phosphorus and nitrogen. Then, the water samples and precipitation water for analysing of dissolved forms of nitrogen and phosphorus and sulphate were filtered through a Whatman GF/F mineral filter of 0.7 μm, whereas the samples for analysing of metals – through a cellulose filter made by Materey company.

Total nitrogen, excluding nitrate, was measured using Kjeldahl method, through sample mineralization with sulphuric acid, and total phosphorus – through mineralization with perchloric acid (Golterman 1969). Ammonium nitrogen was analysed with phenate method, and inorganic dissolved phosphorus – with stannous chloride method (Standard Methods... 1992). Nitrate was measured after nitrate reduction to nitrite with use of hydrazine sulphate, and then by measuring nitrite concentration with use of the method with sulphanilinic acid (Hermanowicz et al. 1976). Concentrations of dissolved organic N and P were calculated from the difference between total and inorganic forms of the elements, whereas concentrations of particulate forms of these elements – from the difference between the concentrations in non-filtered samples and samples filtered through the mineral filter. Sulphate sulphur was assessed using nephelometric method with barium chloride, and metals – calcium, magnesium, potassium and sodium – by flame technique of atomic absorption method, and iron and manganese – by electrothermic method (Standard Methods ... 1992) with use of a Unicam analyser. Heavy metals: zinc, copper, lead and cadmium, were analysed using the method of inverse voltamperometry with standard addition (DPASV) after sample filtration through a teflon filter of 0.45 μm and UV mineralization. To stabilise pH of the samples, nitric acid (Fluka Reagents) was used. Analyses of Zn, Cu, Pb and Cd were made with use of an automated analyser Methrom 646 VA Processor, 675 VA Sample Changer, Switzerland.

3.3. METHODS OF STATISTICAL ANALYSES

In order to find hydrochemical and hydrologic factors affecting retention of mineral components in the transitional peatland, and to assess how these factors influence losses of various forms of essential elements from the peatland, correlation was applied as well as multiple regression method with stepwise selection of independent variables (Guilford 1960, Afifi and Clark 1990). Statgraphics software release 4.0 was used. Conditions, under which the following mineral components: phosphate phosphorus (PO_4-P), ammonium nitrogen (NH_4-N),), nitrate nitrogen (NO_3-N), sulphate sulphur (SO_4-S), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na) and manganese (Mn) are being retained, were analysed. Components that accelerate eutrophication were assumed to be primarily mineral forms of phosphorus and nitrogen (PO_4-P, NH_4-N and NO_3-N), as well as dissolved organic (phosphorus – DOP and nitrogen DON) and particulate (phosphorus – PP and nitrogen – PN) forms, the latter ones being a potential source of eutrophication.

The same hydrochemical and hydrologic parameters were introduced as independent variables to the analysis of factors responsible for retention of elements in the peatland with bog and for losses of eutrophying components from examined peatlands. The hydrochemical factors included concentrations of PO_4-P, NH_4-N, NO_3-N, SO_4-S, ions of Ca, Mg, K, Na, Mn and hydrogen ion (H) in atmospheric precipitation. From among hydrologic factors, precipitation sums, water inflow from the catchment area and evapotranspiration combined with changes in water storage were chosen to the analysis.

To get more reliable results, numerous measures were taken allowing to overcome difficulties in regression analysis of non-experimental data (Box et al. 1978). Most of all, assumed minimum value of F statistics to enter was 6, and independent variables having significance level $p > 0.001$ were eliminated from the regression model. Such variables were included into the equation only when their elimination caused the remaining variables to lose markedly significance in the analysed relationship or in the case when only one independent variable was left in the equation. In order to overcome problems of intercorrelation among independent variables (Afifi and Clark 1990), concentrations of mineral components were used instead of the loads. This is because elemental loads, as being products of concentrations and water flows, are usually interrelated or correlate with the hydrologic parameters. Furthermore, by using a correlation matrix, independent variables which correlated with other variables at $p > 0.01$, and the presence of which in the equation seemed to be less plausible from the hydrochemical point of view, were eliminated from the stepwise selection model.

4. RESULTS

4.1. HYDROCHEMICAL CHARACTERISTICS OF WATER INPUT TO AND OUTPUT FROM THE PEATLANDS

A comparison of hydrochemical data on waters entering and leaving the examined peatland systems is given in Table 2. Bulk precipitation (wet and dry deposition) has a fairly high pH, which presumably results from relatively high contents of calcium and sodium cations (more than 1 mg l^{-1}), these originating from drifting of soil particles from adjacent agricultural areas. On the other hand, precipitation water contained fairly large amounts of sulphur – 0.79 mg SO_4-S l^{-1}. Predominance of dissolved organic and particulate nitrogen among nitrogen species should also be noticed (Table 2A). Generally, the results obtained do not indicate precipitation to has been contaminated.

As mentioned, inland waters supplying the peatland systems under study originate from various environments. These are forest streams, drainage ditches and subsurface waters. Thereby, flow conditions are diversified. Mean flow volumes are higher in watercourses (Table 2 A). Oxygen concentration in the waters varied little, the ranges during the spring period having been 4.4–6.9 for water courses and 2.8–5.2 mg O_2 l^{-1} for shallow subsurface waters (unpublished data).

Contents of N and P of the waters were clearly diversified. The highest concentrations of various phosphorus species and ammonium were recorded in waters derived from the forest and meadow-forest watersheds. Waters flowing out of the agricultural catchments had, in turn, high concentrations of nitrate and dissolved organic nitrogen (Table 2A). When compare with the forest catchments, the waters were also characterised by substantially higher concentrations of SO_4-S (Table 2A) and, to a lower degree, those of Ca, Mg, K and Cu (Table 2B).

4.2. WATER FLOW THROUGH THE HYDROLOGICALLY MODIFIED PEATLANDS

Hydrologic conditions of element fluxes vary considerably among the examined peatland systems. Water budgets are dominated by inflows from the catchments and outflows, both exceeding atmospheric precipitation even from ten to hundred times, as in the case of the modified by channel peatlands with humic lakes (Table 3).

The peatlands differ with regard to yearly evapotranspiration and changes in water storage. The most drained peatland, i.e. the one with deforested catchment used as a meadow, had about two times lower this budget component in comparison with the other systems. This clearly indicates that water is being rapidly lost from the peatland and its storage capacity is low (Table 3). For most peatlands, the synthesised parameter approximates yearly evapotranspiration, because changes in water storage are more or less balanced over a year. However, fluctuations in water storage manifested at the peatland with Pietrzysko lake. Water storage increased here considerably in the second year of the studies due to beaver activity, which retarded water flow (Kruk 1997b) (Table 3).

Hydrological conditions prevailing in consecutive years of the studies were fairly variable. Despite fairly high precipitation sums (about 650 mm yr^{-1}), the period 1992 – 1993 was not abundant in water because of summer drought in 1992. Then, in 1996, an

Table 2. Characteristics of water flow, pH and concentrations of nitrogen, phosphorus and sulphur forms –A and metals – B in water flowing in and out of the exam peatlands. n – number of samples, m- arithmetic mean, SD – standard deviation.

A

	Water type	n	pH (range)	Mean ± SD	Discharge ($m^3 s^{-1}$)	NH_4-N	NO_3-N	DON ($mg\ l^{-1}$)	DTN	PN	PO_4-P	DOP	DTP ($\mu g\ l^{-1}$)	PP	SO_4-S ($mg\ l^{-1}$)
Inflows	From the atmosphere	48	5.5–7.5	m	–	0.49	0.22	0.80[a]	1.53[a]	0.60[a]	22.8	10.1	32.9	27.7	0.79
				SD		0.41	0.28	1.36	1.58	1.05	23.5	12.0	26.7	34.1	0.61
	Forest stream	72	7.1–8.2	m	0.149	0.14	1.57	0.81[b]	2.64[b]	0.24[b]	31.5	19.2	50.7	51.5	8.79
				SD	0.141	0.13	1.90	0.59	1.97	0.38	25.2	22.7	42.0	63.3	3.64
	Stream rising in a mesotrophic lake	48	7.5–8.2	m	0.898	0.12	0.94	0.59[a]	1.80[a]	0.14[a]	10.1	11.2	21.2	12.8	8.10
				SD	0.356	0.15	1.63	0.46	1.69	0.19	7.0	13.5	14.5	19.2	3.43
	Forest subsurface water	48	6.7–8.5	m	0.055	0.28	0.29	0.43	1.00	–	32.3	11.0	43.3	–	8.94
				SD	0.062	0.11	0.19	0.44	0.52		14.8	11.8	19.8		4.67
	Agricultural drain	48	6.5–8.0	m	0.024	0.09	9.74	0.89[a]	12.11[a]	0.23[a]	17.7	13.3	31.0	54.0	18.23
				SD	0.022	0.11	17.27	0.77	18.17	0.38	13.1	20.4	25.8	86.8	7.72
Outflows	Stream rising in humic lakes	48	7.1–8.4	m	0.223	0.15	1.49	0.78[a]	2.65[a]	0.19[a]	20.2	21.2	41.4	26.8	8.83
				SD	0.138	0.22	2.72	0.56	2.60	0.33	20.8	23.2	39.5	31.0	3.87
	Stream after flow through the bog	48	7.4–8.1	m	0.897	0.10	0.85	0.57[a]	1.64[a]	0.21[a]	8.6	9.7	18.3	15.1	6.46
				SD	0.396	0.10	0.47	0.47	1.60	0.31	5.5	11.1	19.0	23.8	2.57
	Stream rising in a mid-forest meadow	24	7.2–8.1	m	0.117	0.41	0.49	0.71	1.61	0.18	32.2	14.3	46.5	69.5	7.50
				SD	0.057	0.27	0.48	0.60	0.80	0.27	13.6	9.7	20.2	46.9	3.08
	Stream rising in a mid-field meadow	48	7.0–8.1	m	0.136	0.11	5.87	0.89[a]	7.70[a]	0.16[a]	13.0	15.6	28.6	30.8	13.38
				SD	0.089	0.11	8.15	0.67	8.35	0.27	6.1	27.4	27.5	39.9	4.32

[a] n = 42; [b] n = 66

B

	Water type	n	PH (range)	Mean ±SD	Discharge ($m^3 s^{-1}$)	Ca	Mg	K	Na	Fe	Mn	Zn	Cu	Pb	Cd
						(mg l^{-1})					(µg l^{-1})				
Inflows	From the atmosphere	48	5.5–7.5	m	–	1.4	0.31	0.58	1.63	0.03[c]	16.0	61.9[c]	3.21[c]	2.61[c]	0.28[c]
				SD		1.4	0.55	0.51	1.93	0.05	15.8	57.5	3.40	3.73	0.58
	Forest stream	72	7.1–8.2	m	0.149	60.3	6.70	1.53	5.23	0.26[d]	41.7	3.9[d]	1.94[d]	0.32[d]	0.05[d]
				SD	0.141	17.8	1.60	0.74	1.79	0.28	52.4	1.9	1.56	0.23	0.10
	Stream rising in a mesotrophic lake	48	7.5–8.2	m	0.898	37.3	8.85	2.25	5.40	0.07[c]	17.6	3.0[c]	1.49[c]	0.36[c]	0.03[c]
				SD	0.356	7.7	1.60	0.80	1.77	0.09	10.5	1.3	0.53	0.40	0.05
	Forest subsurface water	48	6.7–8.5	m	0.055	62.2	7.50	2.00	6.55	0.30	37.2	2.5	1.36	0.16	0.02
				SD	0.062	15.7	2.99	0.62	1.80	0.23	29.2	0.8	1.23	0.14	0.07
	Agricultural drain	48	6.5–8.0	m	0.024	95.1	9.64	2.54	7.73	0.08[c]	27.6	3.7[c]	2.48[c]	0.25[c]	0.03[c]
				SD	0.022	33.9	2.56	1.02	8.11	0.10	23.6	1.7	0.48	0.09	0.05
Outflows	Stream rising in humic lakes	48	7.1–8.4	m	0.223	65.0	7.03	1.40	4.63	0.40[c]	49.9	3.7[c]	1.65[c]	0.26[c]	0.05[c]
				SD	0.138	19.6	2.18	0.77	1.62	0.28	53.8	2.3	0.49	0.16	0.07
	Stream after flow through the bog	48	7.4–8.1	m	0.897	35.8	8.26	2.04	5.15	0.12[c]	30.2	3.0[c]	1.32[c]	0.35[c]	0.02[c]
				SD	0.396	8.0	1.72	0.79	1.54	0.37	38.8	1,0	0.38	0.19	0.05
	Stream rising in a mid-forest meadow	24	7.2–8.1	m	0.117	58.0	5.56	1.95	5.88	0.58	68.1	2.8	1.47	0.21	0.03
				SD	0.057	17.0	1.03	0.68	1.44	0.64	37.2	1.1	0.54	0.10	0.05
	Stream rising in a mid-field meadow	48	7.0–8.1	m	0.136	97.9	10.69	2.13	6.85	0.26[c]	68.1	2.4[c]	1.63[c]	0.12[c]	0.02[c]
				SD	0.089	29.2	2.43	0.72	1.46	0.26	60.1	0.9	0.57	0.10	0.03

[c] n = 24; [d] n = 48

Table 3. Components of the yearly water budget for hydrologically modified peatlands of the Masurian Lakeland in 1992–1996 years. Mean ± mean deviation (n = 2) or standard deviation (n = 4). On the basis of Kruk 1997b, c, d, e and author's unpublished data

Hydrologic component	Peatland with eutrophied humic lake Pietrzysko 6.7 ha (n = 2)		Peatland with eutrophied humic lake Żabie 1.6 ha (n = 2)		Peatland with eutrophied transitional bog 60.5 ha (n = 4)		Drained peatland with meadow in forest landscape 16.7 ha (n = 2)		Drained peatland with meadow in agricultural landscape 38.1 ha (n = 4)	
	$m^3\ yr^{-1}$	$mm\ yr^{-1}$	$m^3\ yr^{-1}$	$mm\ yr^{-1}$	$m^3\ yr^{-1}$	$mm\ yr^{-1}$	$m^3\ yr^{-1}$	$mm\ yr^{-1}$	$m^3\ yr^{-1}$	$mm\ yr^{-1}$
Precipitation	36 984 9 246	552 138	10 432 496	652 31	364 210 67 760	602 112	92 184 23 046	552 138	229 362 45 339	602 116
Inflow from the catchment	854 183 103 850	12 749 1 550	586 256 94 624	36 641 5914	2 841 080 654 005	4 696 1081	371 241 82 498	2 223 494	316 611 89 154	831 234
Outflow in stream water	825 909 141 303	12 327 2 109	585 568 95 984	36 598 5 999	2 835 030 686 070	4 686 1 134	369 571 129 258	2 213 774	429 768 106 680	1 128 280
Evapo-transpiration + Δ storage	65 258 28 207	974 421	10 656 368	666 23	370 865 52 030	613 86	93 854 23 714	562 142	116 205 28 956	305 76

apparent drop to 400 mm in precipitation occurred, and additionally, hydrology of that year was greatly affected by long winter with snow cover persisting until late April followed by rapid thawing (data of meteorologic station in Mikołajki, Kruk 1997b, c). The weather conditions caused hydrological components examined to vary considerably among consecutive years of the study. Mean deviations or standard deviations were usually higher than 20% (Table 3).

4.3. ELEMENTAL FLUXES THROUGH THE HYDROLOGICALLY MODIFIED PEATLANDS

4.3.1. FLUXES OF NITROGEN, PHOSPHORUS AND SULPHUR

Components contained in water showed a strong tendency to have balanced (inflow = outflow) fluxes through the peatlands. This was an effect of ecotonal nature of the peatlands, hydrologic conditions of elemental flows described above, and most of all, predominance of water inflow from the catchment areas.

In the most open modified peatlands under study (regarding inflows and outflows of running waters), i.e. those with humic lakes and transition bog, where element input from the atmosphere is of minor importance, total nitrogen tends to decline in outflowing waters only slightly. This is expressed by 12–17% retention, though absolute values may reach even about 200 kg of N ha^{-1} yr^{-1}, as in the case of Żabie lake (Table 4). Among nitrogen forms, these mires consistently retain only ammonium. The amount of 3.0–6.5 NH_4-N kg ha^{-1} yr^{-1} may be retained, which constitutes up to 40% of input to the peatland with transitional bog (Table 4). The peatlands incised with watercourses did not show any symptoms of greater nitrogen losses.

A little different pattern of nitrogen flow was observed in the drained peatlands with meadows. Nitrogen fluxes are balanced, although nitrate tends to be leached here in a more evident way: about 3 kg of this element ha^{-1} yr^{-1} have been lost by the drained mid-forest peatland. Contrary, retention of NH_4-N is high (about 70%) in the case of the peatland in agricultural area (Table 4).

A pattern of phosphorus fluxes through both peatlands with humic lakes is quite similar. No evident tendencies to retain phosphate phosphorus could be found (7 and 16% of retention, respectively) but considerable losses of organic phosphorus reaching 1.7–1.9 kg ha^{-1} yr^{-1}, and less consistent losses of particulate phosphorus were recorded (Table 4). As a consequence, balances of total phosphorus are negative, which means that the peatlands add to the hydrographic system some 1.4 – 1.8 kg of P ha^{-1} yr^{-1}. Thus, till 20% of the total P input to the mires is being lost (Table 4).

A different pattern of phosphorus flux was found in the case of the peatland with transitional bog, where all P forms were retained to a moderate extent, with PO_4-P having been retained to the highest degree (37%). The peatland with transitional bog retains about 0.6 kg of total phosphorus ha^{-1} yr^{-1}, which constitutes about one third part of the total element input derived mainly from the catchment area (Table 4).

In the drained peatlands, phosphorus fluxes are still different. Phosphate retention is more evident here, reaching up to about 60% of its input at the mid-field meadow, fluxes of organic phosphorus are more balanced, and losses of particulate phosphorus are very high (almost tripled in relation to input at the mid-forest peatland) (Table 4). It appeared that the drained peatland can enrich outflow in about 1 kg of P ha^{-1} yr^{-1} (Table 4).

Balances of SO_4-S, the ion easily transported in aquatic environment, in the modified mire systems studied with inflows and outflows, i.e. those with humic lakes, are consistently balanced (Table 4). The ion tended to be moderately retained in the peatland with transitional bog, and in the drained mid-forest peatland (about 20%). Such a tendency was not found for the more deeply drained peatland in the agricultural landscape (Table 4).

Table 4. Annual retention of nitrogen, phosphorus and sulphur forms in the peatlands. Mean ± mean deviation (n = 2) or standard deviation (n > 2) from n years of the study in the period 1992–1996 (kg ha^{-1}year^{-1}). On the basis of Kruk 1997b, c, d, e and unpublished author's data.

Peatland	Balance components	NH_4-N	NO_3-N	DON	DTN	PN	TN	PO_4-P	DOP	DTP	PP	TP	SO_4-S
With eutrophied humic lake Pietrzysko 6.7 ha	Atmospheric inflow (p)	2.9 0.3	1.4 0.6	6.8 0.8	11.1 1.7	4.1 0.1	15.2 1.8	0.15 0.08	0.05 0.003	0.20 0.08	0.19 0.04	0.39 0.11	4.9 1.0
	Inflow from the catchment (w)	25.8 0.7	169.1 11.9	119.6 62.3	314.5 73.4	32.1 4.3	346.6 77.7	3.53 0.19	1.40 0.95	4.93 1.14	3.66 1.70	8.59 0.56	1136.4 523.0
	Outflow (o)	25.7 0.6	154.4 68.0	105.7 23.9	285.8 43.5	32.6 5.5	318.4 38.0	3.41 0.08	3.33 1.55	6.74 1.63	4.04 1.50	10.78 3.13	1119.3 504.5
(n = 2)	Retention (p + w – o)	3.0 1.0	16.1 80.5	20.7 39.2	39.8 118.6	3.6 1.1	43.4 117.5	0.27 0.19	–1.88 0.61	–1.61 0.44	–0.19 3.16	–1.80 3.58	22.0 19.5
	Retention in % of inflow	**10**	**9**	**16**	**12**	**10**	**12**	**7**	**–130**	**–31**	**–5**	**–20**	**2**
With eutrophied humic lake Żabie 1.6 ha	Atmospheric inflow (p)	2.4 0.6	1.1 0.3	2.9[a]	6.2[a]	1.0[a]	7.2[a]	0.10 0.01	0.07 0.03	0.17 0.04	0.20 0.02	0.37 0.02	3.9 0.2
	Inflow from the catchment (w)	19.0 9.4	897.4 525.2	167.6[a]	1605.5[a]	70.6[a]	1676.1[a]	3.99 1.14	3.73 0.71	7.72 1.84	3.15 0.45	10.87 1.79	3235.8 429.7
	Outflow (o)	14.9 7.0	711.1 508.3	179.5[a]	1406.5[a]	71.6[a]	1478.1[a]	3.45 1.05	5.52 1.56	8.97 2.61	3.69 0.66	12.66 3.26	3125.2 291.9
(n = 2)	Retention (p + w – o)	6.5 3.0	187.4 17.2	–9.0[a]	205.2[a]	0.0[a]	205.2[a]	0.64 0.10	–1.72 0.83	–1.08 0.88	–0.34 0.21	–1.42 1.45	114.5 138.0
	Retention in % of inflow	**30**	**21**	**–5**	**13**	**0**	**12**	**16**	**–45**	**–14**	**–10**	**–13**	**4**

Peatland	Balance components	NH_4-N	NO_3-N	DON	DTN	PN	TN	PO_4-P	DOP	DTP	PP	TP	SO_4-S
With eutrophied transitional bog 60.5 ha (n = 4)	Atmospheric inflow (p)	2.7	1.2	6.4[b]	10.3[b]	3.1[b]	13.4[b]	0.13	0.06	0.19	0.19	0.38	4.4
		0.5	0.5	2.4	2.9	1.4	4.4	0.06	0.02	0.06	0.03	0.08	0.9
	Inflow from the catchment (w)	6.4	60.1	30.2[b]	110.9[b]	6.7[b]	117.6[b]	0.54	0.58	1.12	0.46	1.58	371.0
		4.4	26.4	9.2	18.1	4.0	12.4	0.34	0.35	0.60	0.26	0.49	133.7
	Outflow (o)	5.3	54.6	28.3[b]	100.2[b]	8.1[b]	108.3[b]	0.42	0.47	0.89	0.51	1.40	296.5
		4.1	24.5	9.4	12.1	1.1	10.1	0.23	0.22	0.40	0.19	0.25	65.7
	Retention (p + w – o)	3.8	6.7	8.3[b]	21.0[b]	1.7[b]	22.7[b]	0.25	0.17	0.42	0.14	0.56	78.9
		2.3	3.8	6.0	7.5	3.6	6.2	0.16	0.15	0.26	0.31	0.43	116.4
	Retention in % of inflow	**42**	**11**	**23**	**17**	**17**	**17**	**37**	**26**	**32**	**22**	**29**	**21**
Drained with meadow in forest landscape 16.7 ha (n = 2)	Atmospheric inflow (p)	2.9	1.4	6.8	11.1	4.1	15.2	0.15	0.05	0.20	0.19	0.39	4.9
		0.3	0.6	0.8	1.7	0.1	1.8	0.08	0.003	0.08	0.04	0.11	1.0
	Inflow from the catchment (w)	7.6	7.5	11.2	26.3	0.4	26.7	0.81	0.30	1.11	0.21	1.32	200.6
		2.1	2.6	3.3	8.5	0.3	8.8	0.26	0.14	0.40	0.07	0.46	73.0
	Outflow (o)	9.1	12.6	15.7	37.4	4.6	42.0	0.77	0.34	1.11	1.49	2.60	166.4
		0.8	0.9	8.6	10.3	1.4	11.7	0.17	0.06	0.23	0.47	0.70	74.9
	Retention (p + w – o)	1.4	–3.7	2.3	0.0	–0.1	0.1	0.12	0.01	0.20	–1.09	–0.89	39.1
		1.6	2.8	4.6	0.1	1,0	1.1	0.16	0.08	0.24	0.36	0.13	0.9
	Retention in % of inflow	**13**	**–42**	**13**	**0**	**–2**	**0**	**14**	**1**	**15**	**–282**	**–52**	**19**
Drained with meadow in agricultural landscape 38.1 ha (n = 4)	Atmospheric inflow (p)	3.2	1.3	4.7[b]	9.4[b]	3.4[b]	12.8[b]	0.19	0.07	0.26	0.17	0.43	4.6
		0.9	0.5	1.2	2.3	1.7	3.9	0.13	0.02	0.13	0.06	0.08	1.0
	Inflow from the catchment (w)	0.6	63.9	7.2[b]	83.1[b]	0.5[c]	83.6[c]	0.16	0.11	0.27	0.06[c]	0.33[c]	164.1
		0.4	43.0	4.3	48.3	0.4	48.6	0.06	0.06	0.08	0.02	0.10	85.4
	Outflow (o)	1.2	55.5	10.3[b]	82.3[b]	2.1[b]	84.4[b]	0.15	0.20	0.34	0.32	0.68	158.0
		0.9	41.8	4.4	36.5	1.7	35.0	0.06	0.09	0.12	0.11	0.12	51.5
	Retention (p + w – o)	2.6	9.7	1.6[b]	10.2[b]	1.8[b]	12.0[b]	0.20	–0.02	0.19	–0.13[c]	0.06[c]	10.7
		0.5	36.7	2.6	41.6	3.6	42.9	0.18	0.04	0.91	0.10	0.28	49.6
	Retention in % of inflow	**69**	**15**	**14**	**11**	**46**	**12**	**58**	**–9**	**35**	**–59**	**8**	**6**

[a] n = 1 [b] n =3 [c] n =2

4.3.2. FLUXES OF METALS

In most peatland systems examined, fluxes of calcium, magnesium, potassium and sodium, at almost negligible input of the ions from the atmosphere, is balanced between inflow from the catchment area and outflow (Table 5). The only exception comprises losses of Ca and Mg from the drained peatland with a meadow in the agricultural landscape. It appeared that during one year (4-year-mean), about 310 kg of calcium and 35 kg of magnesium may be lost from one hectare of the peatland, which constitutes about 40% and 50% of inputs of the elements from the catchment (Table 5).

Among trace metals, two distinct groups can be distinguished regarding their geochemical properties. The first group includes iron and manganese ions, and the second one – zinc, copper, lead and cadmium. Waters outflowing from the peatlands tend to be enriched in Fe and Mn, this being testified by predominance of negative balances of the ions. No evident losses of the metals occured only from the peatlands with humic lakes (Table 5). Nevertheless, the negative balances of the elements in the remaining peatlands are considerably high: about 2–6 kg of Fe ha^{-1} yr^{-1} and 0.2–0.6 kg of Mn ha^{-1} yr^{-1}. Thus, the losses may be even 3 times higher than their almost exclusive catchment inputs (Table 5).

Inputs of dissolved forms of Zn, Cu, Pb and Cd comprise typically a substantial contribution of atmospheric sources (Table 5). The metals are tightly retained within the examined peatlands. The tendency for metals to accumulate seems to increase gradually from the peatland with humic lake, through the one with transitional bog, to the drained peatlands. The modified mire with a humic lake retains more than 50% of Zn and Pb inputs, while Cu and Cd retention is low (Table 5). The peatland with transitional bog is an important sink for zinc and cadmium, whereas much less significant sink for lead and copper (Table 5). Finally, both drained peatlands accumulated more than 70% of majority metals examined, except for copper, accumulation of which having also been least effective (below 50%) (Table 5).

4.4. FACTORS LEADING TO EUTROPHICATION OF BOG PEATLANDS

Hydrologically modified peatland with bog chosen to the analysis is a typical example of how man activity can influence peatland ecosystems. The bog incised with a water course has undergone visible transformations of the vegetation cover. This consists in expansion of more productive communities (with common reed and scented fern) where naturally occurring *Sphagnum* bog with sedges (*Carex limosae* and *C. rostrarae*) tends towards ombrotrophy (Kruk 1997c). Thus, it is a typical example of succession of bog biocenoses induced by eutrophication.

The peatland with transitional bog is being supplied by a water course, with a fairly constant flow volume, rising some 1.5 km away in a mesotrophic lake Majcz Wielki. The stream water seems to infiltrate partially and seasonally into the peatland massif. Storage capacity of the peatland causes a characteristic time lag of the stored water outflow. In a yearly cycle, this phenomenon appears as a alternately predominance of inflow vs. outflow, and can be termed as "pulsatory" flow (Kruk 1997c). Under such hydrologic conditions, greater retention of all mineral components in the dormant season, except for NH_4-N and Mn, is not surprising (Table 6). During those periods, volumes of water flow and consequently fluctuations in water storage are higher. At the same time, variability in water storage during both seasons is so high that differences in monthly retention of the chemical components are statistically insignificant ($p > 0.05$) (Table 6).

During the growing season, retention of PO_4-P and its availability to the bog plants depend on factors of catchment and atmospheric origin. Phosphate retention is enhanced by higher precipitation carrying phosphate and also hydrogen ions. At the same time, it is stimulated by an increase in phosphate and nitrate concentrations in water inflowing from the catchment area. This relationship has high coefficient of determination $R^2 = 0.79$ (Table 7). Still stronger positive relationship ($R^2 = 0.92$) was found between NH_4-N retention and concentration of this ion in stream water and atmospheric input, and rise of evapotranspiration and water storage. Retention of NO_3-N is significantly dependent on concentration of this ion in stream water inflow only ($R^2 = 0.56$) (Table 7). Generally, it can be said, that eutrophication of the peatland with transitional bog through retention of inorganic N and P forms is most favoured by higher concentrations of these elements in water fluxes from the catchment and the atmosphere, as well as by an increase in atmospheric precipitation of a lower pH.

Sulphur retention by the eutrophied transitional bog during the growing season depends on sulphate concentration in water inflow ($p < 0.0001$). Coefficient of determination for this relationship is $R^2 = 0.58$ (Table 7). Retention of Ca, Mg, Na and Mn significantly increased along with a decrease in nitrate nitrogen concentration in water inflowing from the catchment (Table 7).

Retention of mineral elements during the dormant season affects eutrophication indirectly, by forming a pool of the minerals, which are then made available during the following growing season. Similarly to the growing season, retention of PO_4-P within the transitional bog peatland during the period of dormancy is mostly associated with an increase in phosphate concentrations in precipitation and stream water inputs, as well as with rise of water storage. Overall, the factors listed above correlate with PO_4-P retention at a high level of $R^2 = 0.79$ (Table 7). Retention of NH_4-N does not correlate with the analysed factors. On the other hand, NO_3-N retention depends on SO_4-S concentration in precipitation water. Here, nitrate retention increases with increasing concentration of sulphate, this being testified by the value of determination coefficient ($R^2 = 0.46$) (Table 7). Thus, winter retention of N and P forms within the peatland with bog depends primarily on concentrations of these elements in inflowing waters, as well as on water storage (P retention) and additionally on sulphate concentration in precipitation (N retention).

During the dormant season, sulphate ions are stored within the bog peatland especially when water storage is high, as well as when magnesium decreases its concentration in stream water input. These factors account for 72% of the variability in sulphate retention ($R^2 = 0.72$) (Table 7). Likewise, changes of storage of water is the most important factor controlling retention of the examined metals: Ca, Mg, K and Na within the bog peatland, this being confirmed by high values of coefficient of determination ($R^2 = 0.64$–0.77) (Table 7).

4.5. ROLE OF HYDROLOGICALLY MODIFIED PEATLANDS IN WATER EUTROPHICATION

There is no unequivocal answer to a question concerning the role of peatlands as ecotone systems in eutrophication of aquatic ecosystems supply by running waters. Standard deviations from mean values of particular components of the ecosystem balances (Tables 4 and 5) show that flow of mineral elements through the hydrologically modified peatlands may vary considerably from year to year. Within a yearly cycle, however, the mire systems may either retain biogenic components, NH_4-N and PO_4-P in particular, though to a fairly limited degree, or lose the elements, mostly organic and particulate phosphorus (Table 4). The analysis of monthly retention revealed that all the elements examined may be retained in certain periods, while lost in some others (Kruk 1997b, c, d, e). Thereby, multiple analysis of a variety of hydrologic and hydrochemical factors diversifying N and P inputs to lakes and rivers may be helpful in assessment of environmental causes of water eutrophication, in which peatlands are being involved.

Table 5. Annual retention of metals in the peatlands. Mean ± mean deviation (n = 2) or standard deviation (n > 2) from n years of study in the period 1992–1996.

Peatland	Balance components	Ca	Mg	K	Na	Fe	Mn	Zn	Cu	Pb	Cd
				kg $ha^{-1}yr^{-1}$					g $ha^{-1}yr^{-1}$		
With eutrophied humic lake Pietrzysko 6.7 ha (n = 2)	Atmospheric inflow (p)	7.7	2.6	3.4	10.3	0.2	0.07	376.3	18.3	16.7	1.15
		4.8	2.4	1.0	5.3	0.1	0.01	162.4	11.7	13.5	0.16
	Inflow from the catchment (w)	6804.2	719.8	262.3	767.9	52.8	7.90	570.9	319.5	58.6	3.45
		1356.2	96.6	35.7	98.2	23.5	0.71	173.8	144.9	14.1	3.22
	Outflow (o)	6232.2	644.7	259.3	657.5	48.7	7.80	440.5	206.4	35.6	3.76
		1865.1	136.0	23.6	123.2	8.6	1.51	183.9	54.1	3.3	3.18
	Retention (p + w – o)	579.7	77.7	6.4	120.7	4.3	0.17	506.7	131.4	39.7	0.84
		499.2	37.1	11.3	19.8	14.7	2.22	152.3	102.6	30.8	0.20
	Retention in % of inflow	**9**	**11**	**2**	**16**	**8**	**2**	**53**	**39**	**53**	**18**
With eutrophied humic lake Żabie 1.6 ha (n = 2)	Atmospheric inflow (p)	11.7	1.2	2.9	12.20	–	0.15	–	–	–	–
		4.3	0.2	1.3	8.50		0.04				
	Inflow from the catchment (w)	26485.7	3116.2	307.4	1469.5	–	6.57	–	–	–	–
		1926.6	403.7	9.4	69.6		1.86				
	Outflow (o)	27689.9	3019.2	315.7	1467.7	–	7.51	–	–	–	–
		4000.8	407.8	5.8	66.2		1.71				
	Retention (p + w – o)	–1192.5	98.2	–5.4	14.0	–	–0.79	–	–	–	–
		2069.9	4.0	16.5	5.1		3.53				
	Retention in % of inflow	**–5**	**3**	**–2**	**1**	**–**	**–12**	**–**	**–**	**–**	**–**

Peatland	Balance components	Ca	Mg	K	Na	Fe	Mn	Zn	Cu	Pb	Cd
		$kg\ ha^{-1} yr^{-1}$						$g\ ha^{-1} yr^{-1}$			
With eutrophied transitional bog 60.5 ha (n = 4)	Atmospheric inflow (p)	9.8	1.9	3.1	11.2	0.2	0.11	376.3[a]	18.3[a]	16.7[a]	1.15[a]
		5.1	1.8	1.2	7.1	0.1	0.05	162.4	11.7	13.5	0.16
	Inflow from the catchment (w)	1742.8	401.5	110.3	271.1	3.9	0.83	172.3[a]	83.8[a]	18.1[a]	1.43[a]
		371.4	83.2	51.2	128.9	0.5	0.27	36.4	10.8	1.9	1.43
	Outflow (o)	1728.5	375.2	101.3	262.5	8.5	1.49	177.5[a]	78.2[a]	19.5[a]	0.96[a]
		367.1	64.1	44.3	116.0	7.0	0.76	40.9	13.1	6.1	0.92
	Retention (p + w – o)	24.1	28.2	12.1	19.8	–4.4	–0.56	371.1[a]	23.9[a]	15.3[a]	1.62[a]
		73.5	24.4	8.6	15.8	6.6	0.52	158.0	9.4	5.6	0.67
	Retention in % of inflow	**1**	**7**	**11**	**7**	**–107**	**–60**	**68**	**23**	**44**	**63**
Drained with meadow in forest landscape 16.7 ha (n = 2)	Atmospheric inflow (p)	7.7	2.6	3.4	10.3	0.2	0.07	376.3	18.3	16.7	1.15
		4.8	2.4	1.0	5.2	0.1	0.01	162.4	11.7	13.5	0.16
	Inflow from the catchment (w)	1249.8	140.1	41.0	121.3	7.4	0.98	64.6	38.5	4.0	0.65
		241.9	9.4	5.5	27.4	0.6	0.42	21.0	0.4	1.0	0.57
	Outflow (o)	1310.5	117.3	41.8	133.2	13.4	1.45	68.7	35.4	5.0	0.75
		487.2	33.1	6.8	47.9	1.8	0.15	32.2	16.7	2.4	0.70
	Retention (p + w – o)	–53.0	25.4	2.6	–1.6	–5.8	–0.40	372.2	16.4	15.7	1.05
		240.5	21.3	0.4	15.2	2.2	0.27	151.3	0.3	12.1	0.03
	Retention in % of inflow	**–4**	**18**	**6**	**–1**	**–76**	**–38**	**84**	**29**	**76**	**58**
Drained with meadow in agricultural landscape 38.1 ha (n = 4)	Atmospheric inflow (p)	14.7	2.1	4.0	11.0	0.4	0.12	239.7[a]	13.0[a]	15.9[a]	0.57[a]
		5.9	1.8	1.5	6.5	0.3	0.04	106.1	2.2	14.2	0.17
	Inflow from the catchment (w)	787.9	76.0	22.8	61.0	0.5	0.18	35.9[a]	24.0[a]	1.8[a]	0.47[a]
		243.9	17.8	7.4	18.5	0.2	0.03	20.5	10.0	0.5	0.40
	Outflow (o)	1111.8	114.5	24.1	75.8	3.0	0.49	28.4[a]	19.4[a]	0.9[a]	0.27[a]
		346.4	26.6	5.0	22.0	0.7	0.22	17.1	6.9	0.5	0.27
	Retention (p + w – o)	–309.2	–36.4	2.7	–3.8	–2.1	–0.19	247.2[a]	17.6[a]	16.8[a]	0.76[a]
		137.8	14.5	4.3	8.1	0.6	0.21	102.6	5.3	14.7	0.29
	Retention in % of inflow	**–39**	**–47**	**10**	**–5**	**–233**	**–63**	**90**	**48**	**95**	**74**

[a] n = 2

Table 6. Monthly retention of elements (kg ha^{-1} $month^{-1}$) in the peatland with eutrophied transitional bog during four growing seasons (May – October) and four dormant seasons (November – April). m – mean, SD – standard deviation, p – significance level of the differences between means according to t-test.

Element		PO_4-P	NH_4-N	NO_3-N	SO_4-S	Ca	Mg	K	Na	Mn
Growing season	m	0.0186	0.465	0.435	7.16	–3.79	0.67	0.52	0.85	–0.084
n = 24	± SD	0.0208	0.621	1.444	21.27	29.44	6.02	2.28	4.88	0.229
Dormant season	m	0.0222	0.178	0.727	10.27	11.93	4.02	1.50	1.81	–0.009
n = 24	± SD	0.0198	0.438	3.662	22.31	52.31	10.77	4.15	10.96	0.061
p		> 0,05	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05

4.5.1. HYDROCHEMICAL LINKAGES OF PHOSPHORUS IN THE STREAM WATER RUNOFF

It can be said that peatlands subjected to modifications of their hydrologic systems will tend to become hydrologically homogenous, regardless of whether the mire plant community has changed radically (due to drainage) or partially (due to incomplete drainage). Such a picture was observed in the investigated systems having clear inflow and outflow, although a number of secondary differences in their hydrology appeared (Chapter 4.1.). Acceleration of water flow from the catchment area means that phosphorus interactions in runoff can be expected to resemble those characteristic of peatland waters, as well as waters from drained catchment. Cooccurrence of phosphorus forms and Fe ions in outflowing water indicates P leaching from mineral Fe – Al complexes, this being typical of mire habitats. Furthermore, a high correlation between loads of phosphate and particulate phosphorus and quantities of calcium exported in water runoff points out mineral origin of P, the element being leached from apatite minerals at pH = 7 (Mitsch and Gosselink 1993).

Indeed, phosphate phosphorus efflux from studied peatlands was clearly correlated with that of iron (R^2 = 0.46) (Fig. 3). A similar regression curve was also fitted to the relationship between PO_4-P and Ca outputs, and the correlation was even stronger (R^2 = 0.54) (Fig. 4). The same patterns were found for particulate phosphorus relations with effluxes of the two metals: Fe (R^2 = 0.50) (Fig. 5) and Ca (R^2 = 0.54) (Fig. 6). Thus, a mutual interaction occurs in the examined peatlands between phosphorus pool carried with iron and that transported together with calcium. It should be emphasised that the relationships explain about 50% of variability in the dependent variable. It thus indicates that the peatlands differ among each other with regard to hydrochemical properties of outflowing waters. At the same time, it suggests that some additional factors control over the loads of the analysed mineral components. To answer the question about what kind of geochemical environment, peatlands themselves or mineral substrate of their catchments, influences more the losses of mineral and particulate P from particular systems, multiple regression can be applied where P load in stream water runoff is the dependent variable, whereas independent variables include Fe and Ca effluxes.

It turned out that in the peatland with humic lake only efflux of dissolved inorganic phosphorus was significantly correlated with that of iron, which indicated considerable importance of this mire system for phosphate outflow. No statistically significant correlations ($p > 0.05$) between calcium and PO_4-P or between either of the two metals and particulate phosphorus losses were found (Table 8). Similarly, in the water course moving out of the peatland with the transitional bog and rising in a nearby medium size lake, calcium losses did not influence any phosphorus form, whereas iron losses significantly correlated with outflows of particulate P ($p < 0.01$) (Table 8). The greatest number of statistically significant interrelations between Fe and Ca losses and phosphorus removal were found in the case of the drained peatlands with meadows. Iron and calcium loads in water runoff both significantly influenced phosphate losses ($p < 0.0005$). Moreover, the iron load plays a crucial role in outflow of particulate phosphorus, this being testified by the significance level $p < 0.0001$. On the other hand, the calcium load does not affect PP losses from the drained peatlands (Table 8). It can be generally presumed, that phosphorus losses (as PO_4-P and particulate P) from all examined peatlands are influenced by its internal environment, while an influence of the catchment formed from mineral bedrocks tends to be visible only in drained peatlands with meadows.

4.5.2. FACTORS AFFECTING LOSSES OF PHOSPHORUS AND NITROGEN FROM THE PEATLANDS

As revealed, losses of nutrients from hydrologically modified peatlands in runoff water are affected by hydrochemical interactions resulting from biogeochemical characteristics of the peatlands, as well as from properties of their catchments formed on mineral soils. In systems where the water flow is being artificially "forced", N and P transport is very likely to be affected by the catchment in particular, but also by the atmosphere. Chemical properties and volume of water entering the peatlands would thus control over losses of the elements from the ecosystems. These properties include e.g. nitrogen and phosphorus loads in water inputs from the catchment and the atmosphere, a complex of hydrologic factors, as well as presence of modifying ions in waters supplying the peatlands. Assessment of functioning of the hydrologically modified peatlands as ecotones transferring or bearing eutrophying components is possible only when interactions are known among the factors that determine more comprehensively hydrological and biogeochemical system of the whole watersheds.

The modified peatlands with humic lakes carry out in otflow fairly large quantities of PO_4-P, i.e. about 3.5 kg ha^{-1} yr^{-1}. These are, however, amounts approximating those received by the systems from their own catchments. In a yearly scale, the mire-lake systems may be sources of dissolved organic phosphorus in particular and, to a lesser extent, also particulate phosphorus (Table 4). Phosphate losses increase with increasing water inflow carrying higher loads of PO_4-P and a modifying sodium ion. The larger hydrologic input from the catchment, the higher are losses of organic phosphorus from the peatland. Losses of particulate phosphorus are not influenced by the analysed factors (Table 9).

Losses of another component responsible for eutrophication, namely nitrate ion, increase during periods of low evapotranspiration and lowered water storage in the peatlands, and also when concentration of NO_3-N in water inflowing from the catchment is higher. Ammonium removal, in turn, depends primarily on volume of inflowing water and NH_4-N concentration in the water, whereas losses of DON and particulate N – exclusively on the water volume ($p < 0.002$) (Table 9). To sum up, a leading factor that enhance eutrophication of waters flowing out of the modified peatlands with humic lakes is increased water inflow and thus higher loadings of mineral N and P forms, as well as lowering of water storage.

At the peatland with transitional bog, no negative annual mean balances of N and P were noted (Table 4). The elements exhibited a moderate tendency to retain here. It does

Table 7. Monthly retention of elements (y) in the peatland with eutrophied transitional bog as a function of the element concentration in water inflow from the atmosphere and the catchment, concentrations of modifying elements in the inflow and hydrologic factors (x) during the growing (May – October) and dormant (November – April) season (data from four years, n = 24). Multiple regression function: $y = a + b_1x_1 + ... + b_nx_n$, at treshold value of F = 6.

Season	y Retention of an element (kg ha^{-1} $month^{-1}$)	Intercept a	Slopes of regression bx Significance level *p*							Coeficient of determination
			Element concentration in the water inflow ($mg\ l^{-1}$)		Concentration of modifying elements in the water inflow ($mg\ l^{-1}$)		Hydrologic factors (mm)			
			from the atmosphere	from the catchment	from the atmosphere	from the catchment	precipitation	inflow from the catchment	evapotranspiration and changes in water storage	R^2
Growing	PO_4-P	– 0.040	0.50 *0.0000*	2.41 *0.0008*	14.0(H) *0.0076*	0.0068(NO_3-N) *0.0009*	0.00024 *0.0002*	–	–	0.79
	NH_4-N	– 0.25	0.47 *0.0000*	2.83 *0.0000*	–	–	–	–	0.0024 *0.0006*	0.92
	NO_3-N	– 0.0029	–	0.93 *0.0000*	–	–	–	–	–	0.56
	SO_4-S	– 24.4	–	3.90 *0.0000*	–	–	–	–	–	0.58
	Ca	3.54	–	–	–	– 15.6 (NO_3-N) *0.0011*	–	–	–	0.36
	Mg	2.07	–	–	–	– 2.96 (NO_3-N) *0.0030*	–	–	–	0.30
	K	–	–	–	–	–	–	–	–	0.00
	Na	2.10	–	–	–	– 2.6 (NO_3-N) *0.0007*	–	–	–	0.38
	Mn	– 0.024	–	–	–	– 0.13 (NO_3-N) *0.0006*	–	–	–	0.40

Season	y	a	from the atmosphere	from the catchment	from the atmosphere	from the catchment	precipitation	inflow from the catchment	evapotranspiration and changes in water storage	R^2
Dormant	PO_4-P	– 0.0068	0.62 *0.0000*	1.19 *0.0000*	–	–	–	–	0.000052 *0.0017*	0.79
	NH_4-N	–	–	–	–	–	–	–	–	0.0
	NO_3-N	– 7.12	–	–	0.97 (SO_4-S) *0.0001*	–	–	–	–	0.46
	SO_4-S	43.1	–	–	–	– 4.74 (Mg) *0.0006*	–	–	0.12 *0.0000*	0.72
	Ca	– 9.99	–	–	–	–	–	–	0.33 *0.0000*	0.69
	Mg	– 0.37	–	–	–	–	–	–	0. 067 *0.0000*	0.64
	K	– 0.20	–	–	–	–	–	–	0.026 *0.0000*	0.66
	Na	– 3.08	–	–	–	–	–	–	0.075 *0.0000*	0.77
	Mn	–	–	–	–	–	–	–	–	0.0

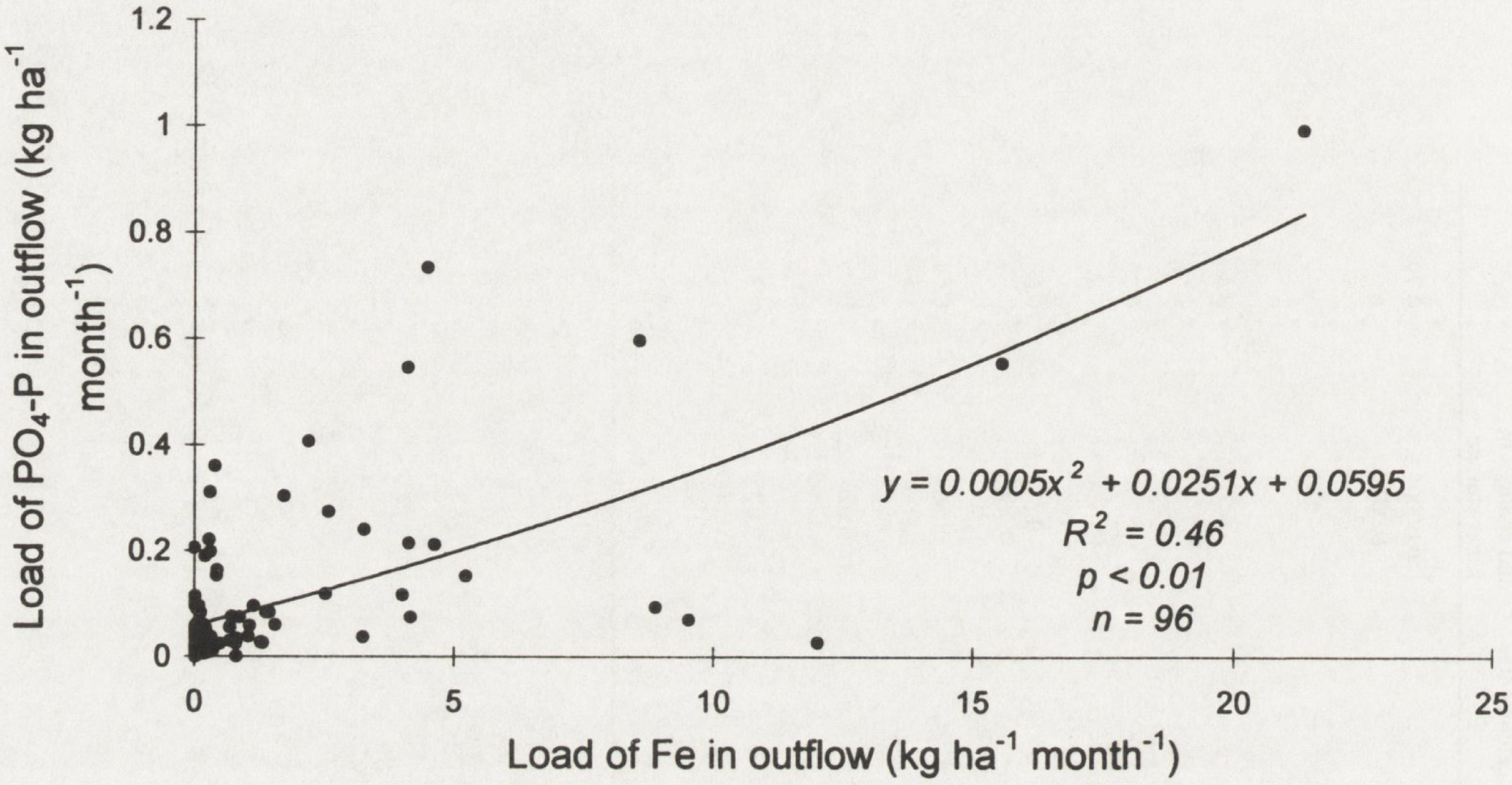

Fig. 3. The relationship between monthly loads of iron and phosphate phosphorus in surface waters outflowing from the five studied peatlands.

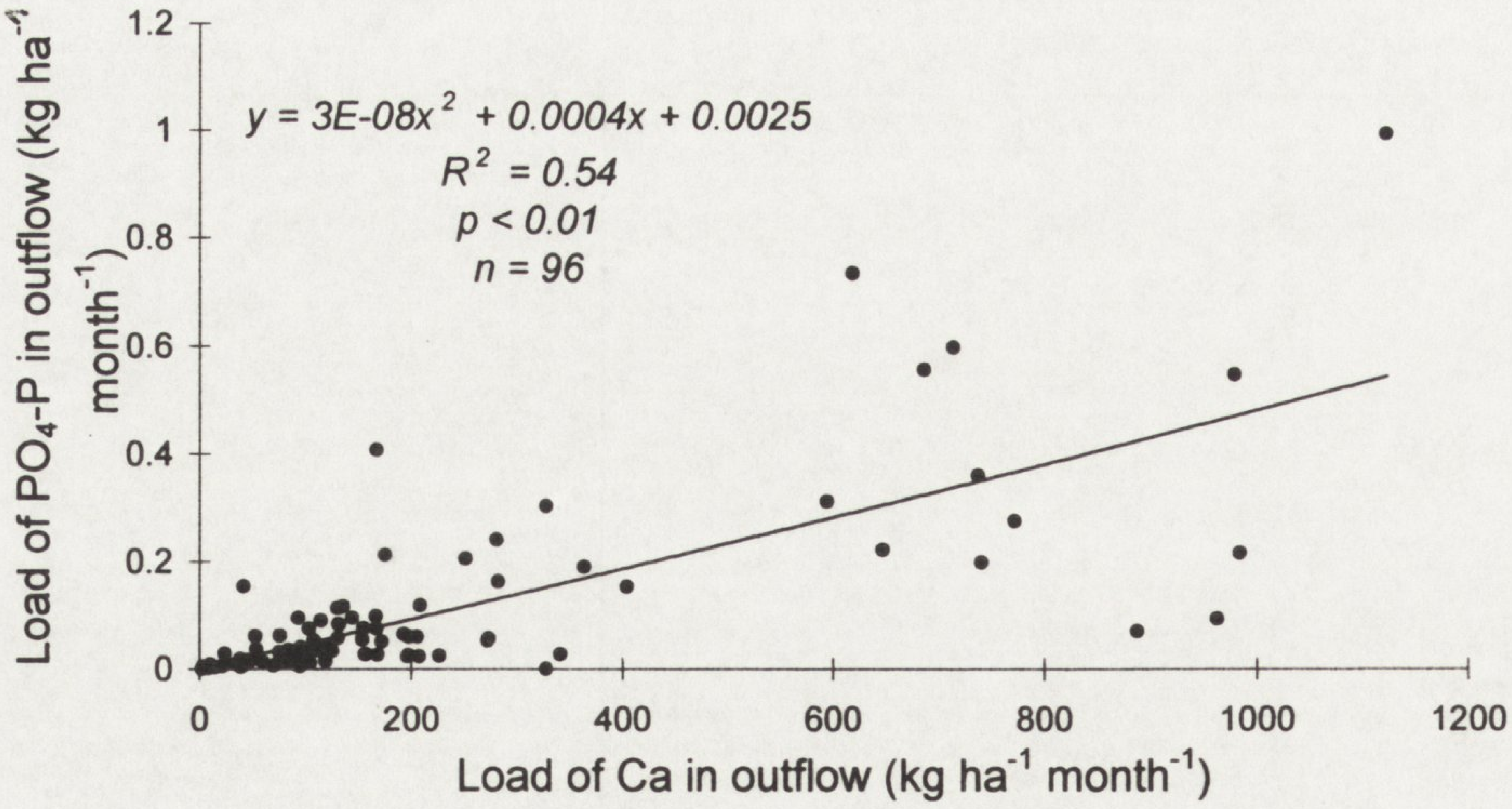

Fig. 4. The relationship between monthly loads of calcium and phosphate phosphorus in surface waters outflowing from the five studied peatlands.

not mean that enhanced losses of the elements in a year or certain period of a year could not have occurred. This is especially true for particulate forms of the elements (Kruk 1997 c). Phosphate losses may increase as an effect of higher PO_4-P concentrations in the water flow, whereas losses of particulate phosphorus increase at higher concentrations of NH_4-N in precipitation and NO_3-N in water inflow from the catchment (Table 9). Similar factors partially influece losses of nitrate and ammonium ions. Both ions may supply waters outflowing from peatland, when their concentrations in water inflowing from catchment are increasing, at simultaneous lowering of water storage.

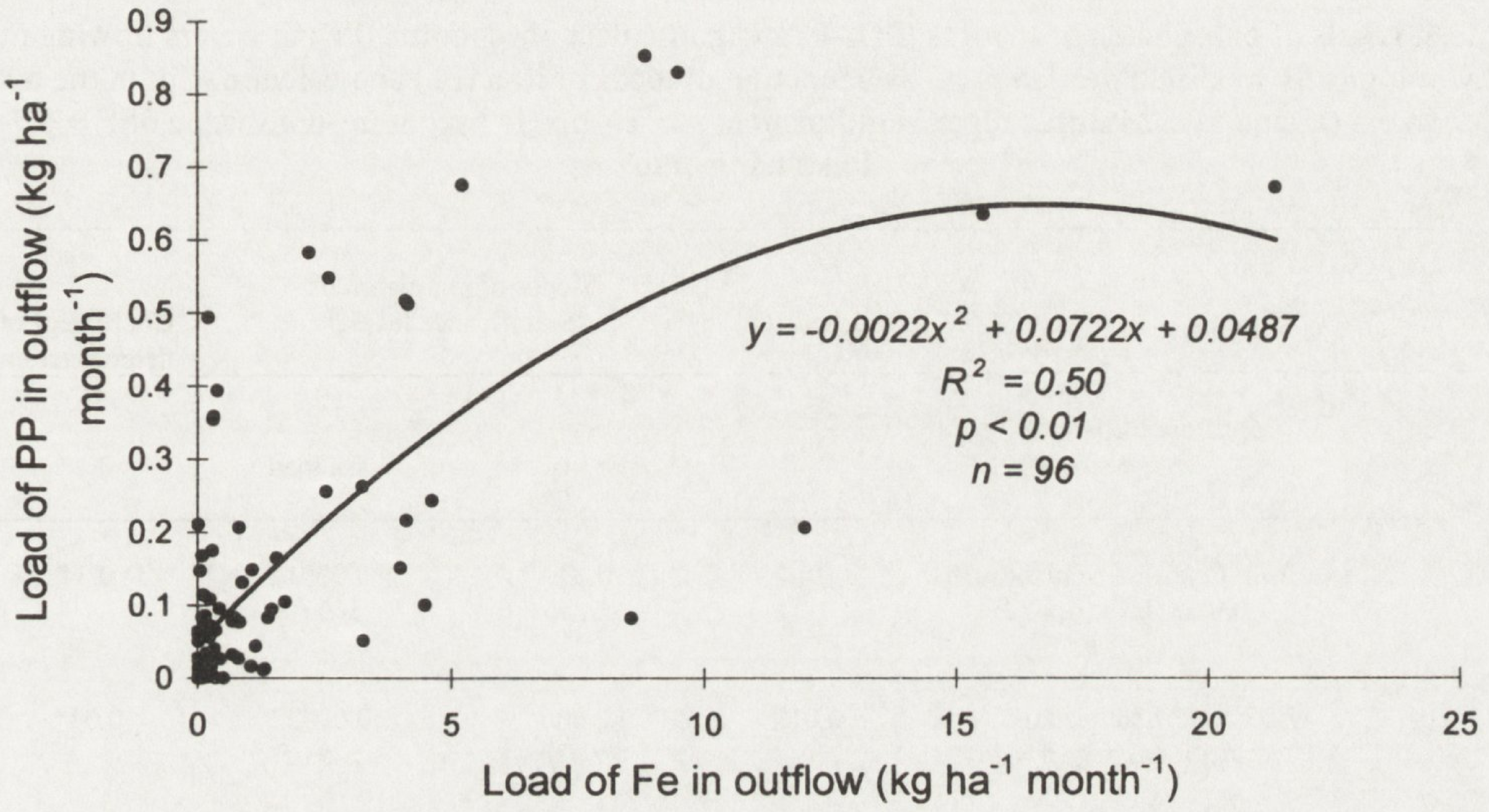

Fig. 5. The relationship between monthly loads of iron and particulate phosphorus in surface waters outflowing from the five studied peatlands.

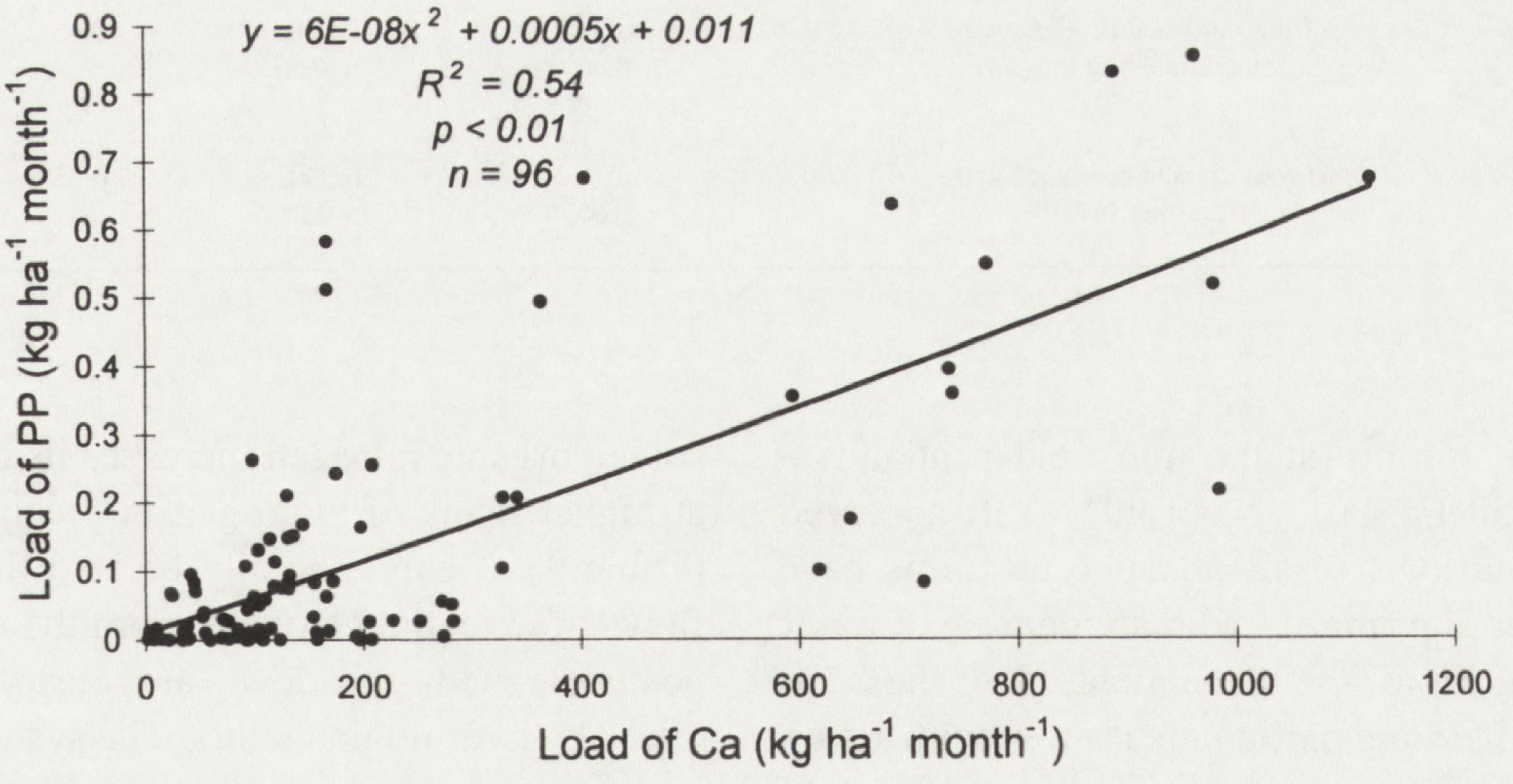

Fig. 6. The relationship between monthly loads of calcium and particulate phosphorus in surface waters outflowing from the five studied peatlands.

Moreover, additional hydrochemical factors such as concentrations of PO_4-P and K in the watercourse and Mg in precipitation may significantly modify the pattern. Losses of DON increase as influenced by low pH of precipitation (Table 9). Generally, losses of essential elements from the eutrophied peatland with bog tend to increase at raised concentrations of the elements in stream water inflow and at lowered water storage.

A comparison of elemental balances indicates that the drained peatlands with meadows may be a source of such components as dissolved organic phosphorus, particulate phosphorus and nitrate ion. Outflow of total phosphorus may reach 2.5 kg ha^{-1} yr^{-1}, and

Table 8. Loads of phosphate phosphorus (PO_4-P) and particulate phosphorus (PP) in waters flowing out of the hydrologically modified peatlands (y) as a function of loads of iron (Fe) and calcium (Ca) in the outflow waters (x_1 and x_2) . Multiple regression function: $y = a + b_1x_1 + b_1x_2$ at treshold value of F = 6. In kg $ha^{-1}month^{-1}$.

y	Outflow loads	Intercept a	Slopes of regression bx Significance level *p*		Coefficient of determination R^2
			x_1 Fe load	x_2 Ca load	
PO_4- P	from modified peatland with humic lake (n = 22)	0.14	0.23 *0.0240*	0.00012 *> 0.05*	0.34
	from modified peatland with transitional bog (n = 24)	0.019	– 0.006 *> 0.05*	0.00022 *> 0.05*	0.04*
	from drained peatlands with meadows (n = 48)	– 0.00054	0.016 *0.0003*	0.0032 *0.0002*	0.56
PP	from modified peatland with humic lake (n = 22)	0.14	0.016 *> 0.05*	0.00028 *> 0.05*	0.28
	from modified peatland with transitional bog (n = 24)	– 0.0062	0.012 *0.0072*	0.0002 *> 0.05*	0.45
	From drained peatlands with meadows (n = 48)	0.0071	0.055 *0.0000*	0.0003 > 0.05	0.55

* insignificant relationship ($p > 0.05$)

that of nitrate (at the mid-field peatland) – even 50 kg ha^{-1} yr^{-1} (Table 4). It appeared that outflows of all phosphorus forms have increased primarily with an increase in water inflow from the catchment, and those of phosphate and particulate P – also with a drop in water storage. Additionally, outflows of PO_4-P may also rise when both concentration of this ion in water input from the catchment and the amount of precipitation increase (Table 9). Somewhat similar set of factors influences outflows of nitrogen forms, except for nitrate, removal of which depends on one hydrochemical factor only, i.e. an increase in potassium concentration in water inflowing from the catchment. Ammonium flow out of the drained peatlands rises when water inflow from the catchment and concentration of the ion in the water are increased, as well as when water storage in the peatland is lowered. Dissolved organic nitrogen increases its outflow at higher loads of hydrogen in precipitation (Table 9). It can generally be said that outflows of essential elements from the drained peatlands with meadows are cleary influenced by hydrologic factors. The systems enhance water eutrophication through increased water input from their catchments, higher precipitation and a drop in water storage. These interactions are additionally modified by higher inputs of K and NH_4-N from the catchment area.

4.5.3. EUTROPHICATION OF PEATLANDS AND PEATLANDS AS SOURCES OF WATER EUTROPHICATION

Acceleration of water cycling through drainage or establishment of correction ditches and channels in a peatland means usually that supply of essential elements to the peatland will be enhanced. A question arises what is the response of the modified natural systems to the more and more increasing nutrient loads? Are the systems a sink that retains the surplus and thus eutrophies its own habitat or loses the extra loads of nutrients, which are then carried to water ecosystems of lower elevations? On the one hand, hydrologic modifications are followed by eutrophication of poorer ecosystems, such as the peatlands with humic lakes or bogs, this being manifest by changes in the vegetation cover. On the other hand, considerable losses and negative budgets, those of phosphorus in particular, have been observed (Chapter 4.3.).

There is a body of evidence, that hydrologically modified peatlands with humic lakes and bogs may be a sink and source of eutrophication at the same time. Drained peatlands with meadows respond to enhanced loads of N and P differently. As yearly input of total nitrogen derived from the catchment and the atmosphere increases, N retention in the peatlands with humic lakes and bogs also increases, this being confirmed by values of coefficient of determination $R^2 = 0.62$ and significance level $p < 0.05$ (Fig. 7A). The increase is not however proportional, which suggests that a threshold value has to exist. Such a consistent increase in nitrogen retention with increasing N input has not been observed in the drained peatlands. The element may be retained here regardless of the level of N input (Fig. 7B).

It is symptomatic, that total phosphorus does not follow the pattern of changes in nitrogen retention in any of the two peatland groups distinguished. Unlike nitrogen, a higher yearly input of phosphorus may be even followed by losses of total P from the peatlands, although the relationship is insignificant for the systems with lakes and bogs (Fig. 8A). Nevertheless, the relationship between P influx and P retention is evident in the drained peatlands with meadows. When P input exceeds 0.8 kg ha^{-1} yr^{-1}, its net retention becomes negative, which means that phosphorus is being lost from the peatlands. The relationship is confirmed by coefficient of determination $R^2 = 0.71$ and significance level $p < 0.01$ (Fig. 8B).

The question is whether all forms of phosphorus tend in more or less pronounced way to be lost from the peatlands at increased P inputs? It appears that the opposite is also possible. At higher total P loadings from the catchment phosphate has been retained with increasing effectiveness in the modified peatlands with humic lakes and bogs. The relationship was significant at $p = 0.05$ and determined by $R^2 = 0.44$ (Fig. 9A). This indicates that the pool of available phosphorus circulating within the peatlands has been enlarged. Furthermore, it means (Fig. 8A) that phosphorus losses from the peatlands with bogs and humic lakes relate to other than phosphates P forms. Enhanced eutrophication pressure on these peatlands is thereby accompanied by a tendency parallel to nitrogen "capturing" and consisting in incorporation of another important nutrient, namely phosphate phosphorus, into the intrasystem cycle. In the drained peatlands with meadows, in turn, increased inputs of total phosphorus result in different levels of phosphate retention (Fig. 9B).

On this background, notice should be taken of a negative relationship between total P input to the modified peatlands with bogs and humic lakes and retention of dissolved organic phosphorus. The relationship has high coefficient of determination $R^2 = 0.81$ and significance level $p < 0.01$ (Fig. 10A). It shows that above certain level of P inputs from the atmosphere and the catchment (about 2 kg ha^{-1} yr^{-1}) one may expect outflowing waters to be enriched in an extra load of phosphorus in the dissolved organic form. Because the load, as is shown in Figures 9A and 10A, exceeds by much quantities of retained PO_4-P, it has to be derived not only from P transformations, but also, in its larger part, from the peatland resources. In the managed drained peatlands, retention of DOP do

Table 9. Monthly effluxes of phosphorus and nitrogen forms (y) as a funtion of the element inflows from atmosphere and the catchment and hydrologic factors (x) from hydrologically modified peatlands. Coefficients of multiple regression $y = a + b_1x_1 + ... + b_nx_n$ at treshold value of F = 6.

Peatlands	y Efflux of an element (kg ha^{-1} $month^{-1}$)	Intercept a	Slopes of regression bx significance level *p*					Coefficient of determination R^2
			Concentration of an element in inflow waters (mg l^{-1})		Hydrologic factors (mm)			
			from the atmosphere	from the catchment	precipitation	inflow from the catchment	evapotranspiration and changes of water storage	
with eutrophied humic lake (n = 48)	PO_4-P	– 0.47	–	15.1(PO_4-P) + 0.058(Na) *0.0000* *0.0000*	–	0.000063 *0.0005*	–	0.61
	DOP	0.11	–	–	–	0.00013 *0.0014*	–	0.18
	PP	–	–	–	–	–	–	0.00
	NO_3-N	– 78.2	–	21.6(NO_3-N) + 15.9(Na) *0.0000* *0.0001*	–	–	– 0.065 *0.0002*	0.62
	NH_4-N	2.93	–	5.49 (NH_4-N) – 0.47(Mg) *0.0000* *0.0002*	–	0.00070 *0.0000*	–	0.49
	DON[a]	0.31	–	–	–	0.0069 *0.0002*	–	0.32
	PN[a]	– 1.43	–	–	–	0.0034 *0.0016*		0.23

Peatlands	y	a	from the atmosphere	from the catchment	precipitation	inflow from the catchment	evapotranspiration and changes of water storage	R^2
with eutrophied transitional bog (n = 48)	PO_4-P	– 0.014	–	4.81(PO_4-P) *0.0000*	–	–	–	0.81
	DOP	–	–	–	–	–	–	0.00
	PP	– 0.021	0.062(NH_4-N) *0.0001*	0.015(NO_3-N) *0.0004*	–	–	–	0.41
	NO_3-N	– 1.45	–	5.18(NO_3-N) + 169.6(PO_4-P) *0.0000* *0.0003*	–	–	– 0.011 *0.0005*	0.94
	NH_4-N	– 0.34	0.81(Mg) *0.0000*	0.93(NH_4-N) + 0.22(K) *0.0008* *0.0001*	–	–	– 0.0015 *0.0005*	0.79
	DON[a]	1.15	1.18(H) *0.0000*	–	–	–	–	0.45
	PN[a]	–	–	–	–	–	–	0.00
drained with meadows (n = 72)	PO_4-P	– 0.023	–	0.70(PO_4-P) *0.0001*	0.00031 *0.0003*	0.00030 *0.0000*	– 0.00033 *0.0000*	0.66
	DOP	0.0045	–	–	–	0.00015 *0.0009*	–	0.13
	PP	0.021	–	–	–	0.00055 *0.0000*	– 0.00064 *0.0002*	0.30
	NO_3-N	– 4.54	–	3.50(K) *0.0000*	–	–	–	0.34
	NH_4-N	– 0.095	–	0.91(NH_4-N) *0.0006*	–	0.0031 *0.0000*	– 0.0024 *0.0008*	0.56
	DON[b]	0.70	0.021(H) *0.0000*	–	–	–	–	0.38
	PN[b]	–	–	–	–	–	–	0.00

[a] n = 36, [b] n = 60

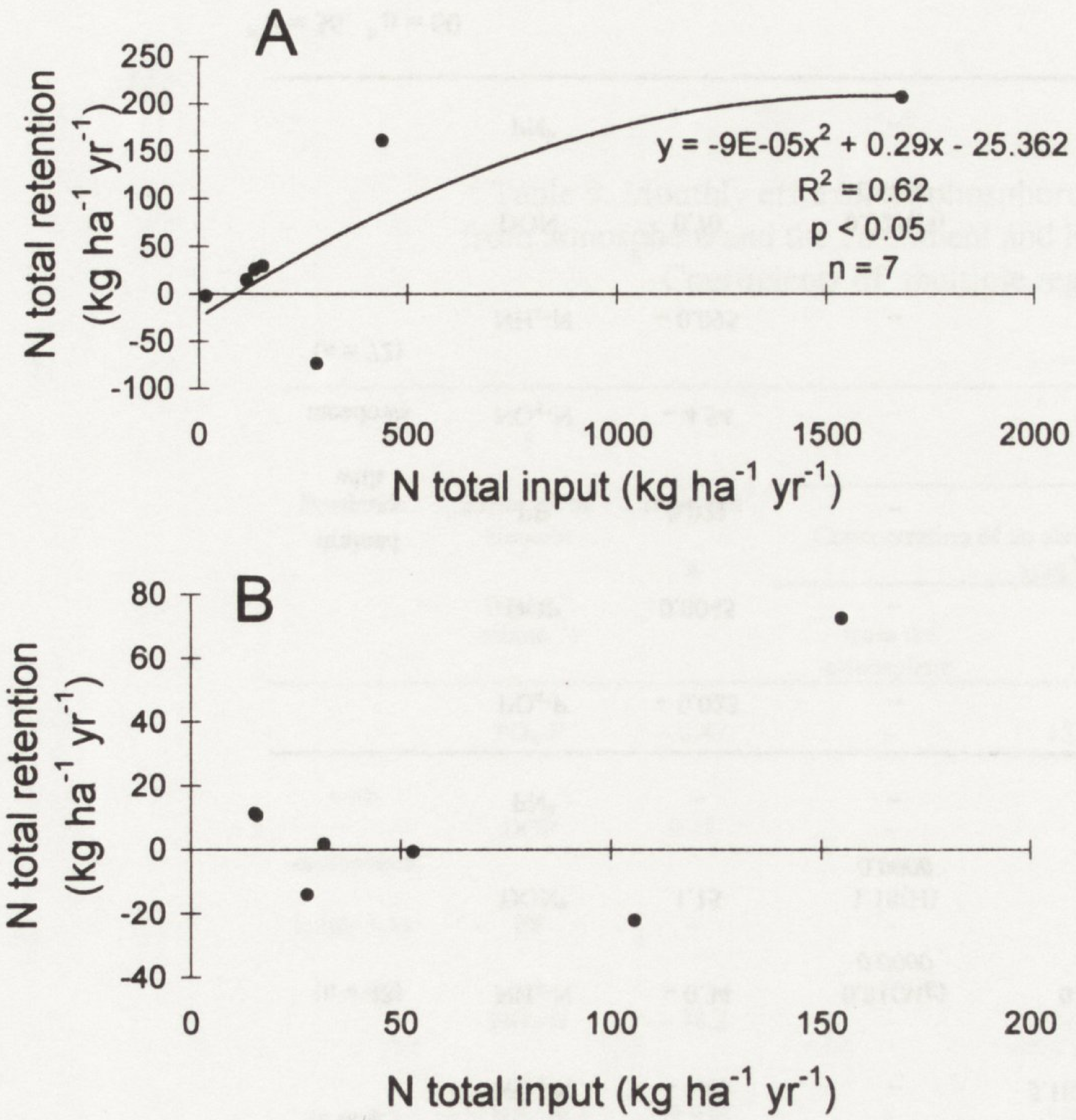

Fig. 7. The effect of total nitrogen input from the catchment and the atmosphere on N retention in hydrologically modified peatlands with small humic water bodies and bogs (A) and in drained peatlands with meadows (B). Data from: Kruk (1998b, c, d, e) (10 sites), Kruk (unpublished) (3 sites), Stachurski and Zimka (1994) (1 site, recalculated).

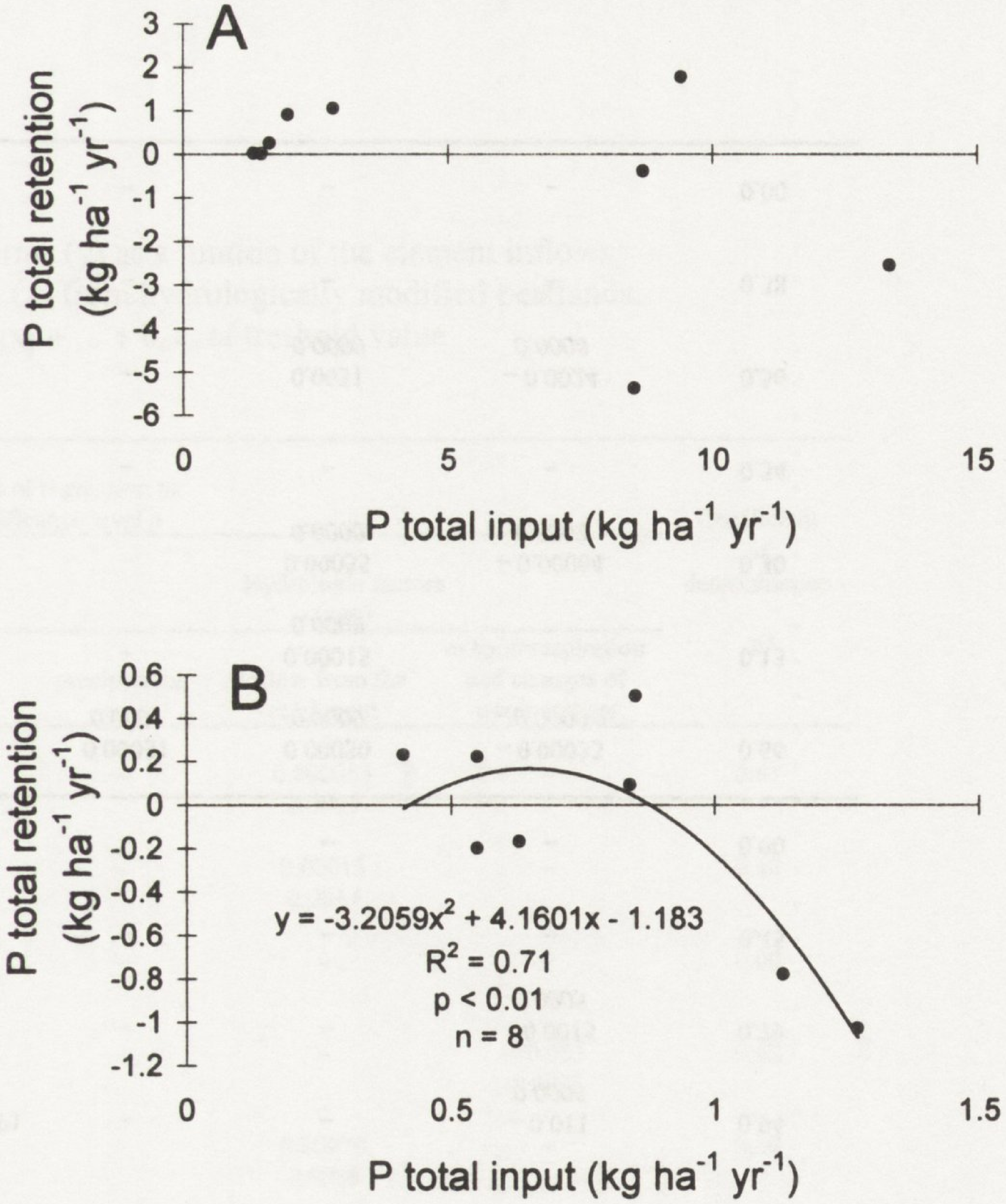

Fig. 8. The effect of total phosphorus input from the catchment and the atmosphere on P retention in hydrologically modified peatlands with small humic water bodies and bogs (A) and in drained peatlands with meadows (B). Data from: Kruk (1998b, c, d, e) (12 sites), Kruk (unpublished) (4 sites), Stachurski and Zimka (1994) (1 site, recalculated).

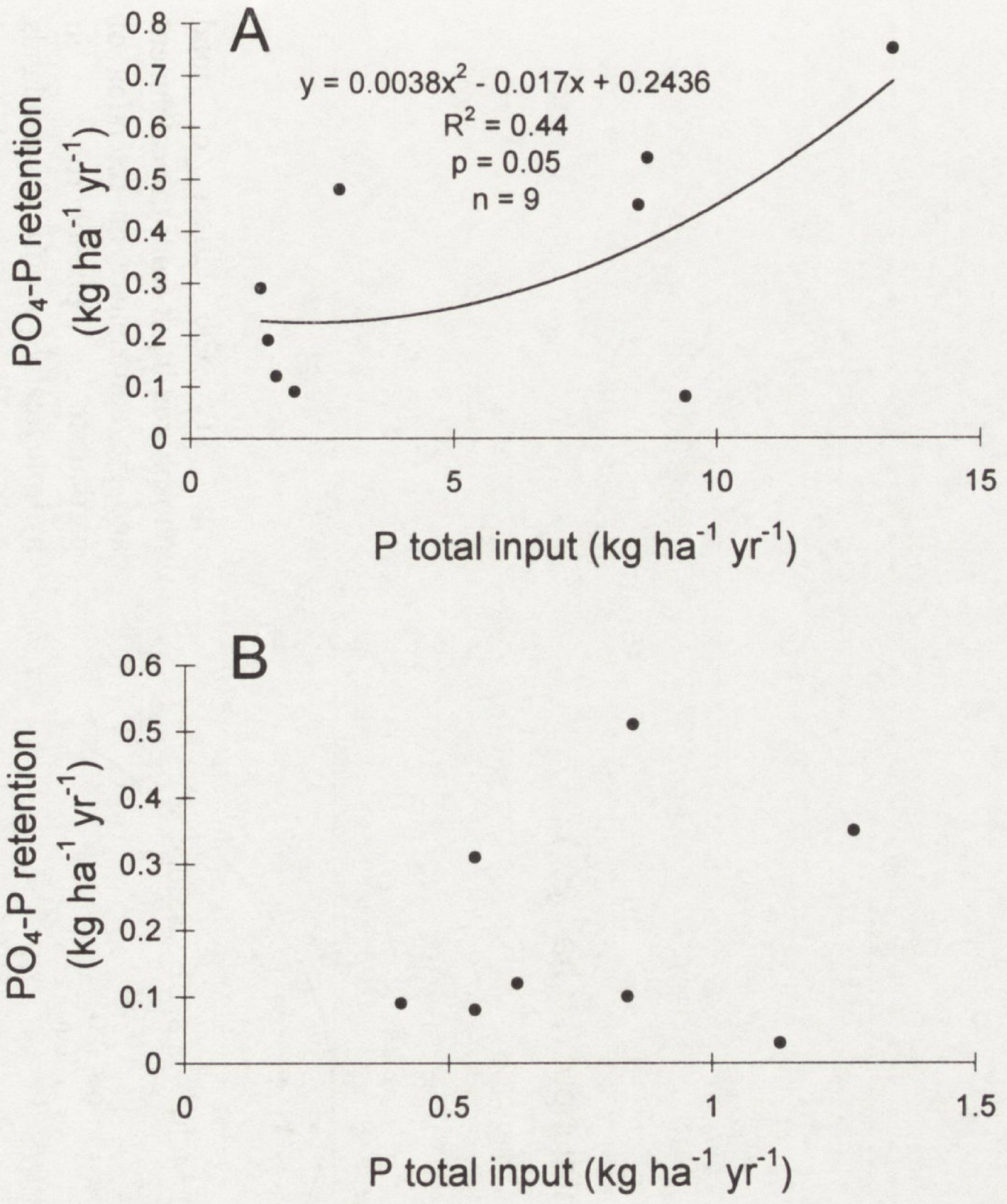

Fig. 9. The effect of total phosphorus input from the catchment and the atmosphere on retention of phosphate phosphorus in hydrologically modified peatlands with small humic water bodies and bogs (A) and in drained peatlands with meadows (B). Data: see Fig. 8.

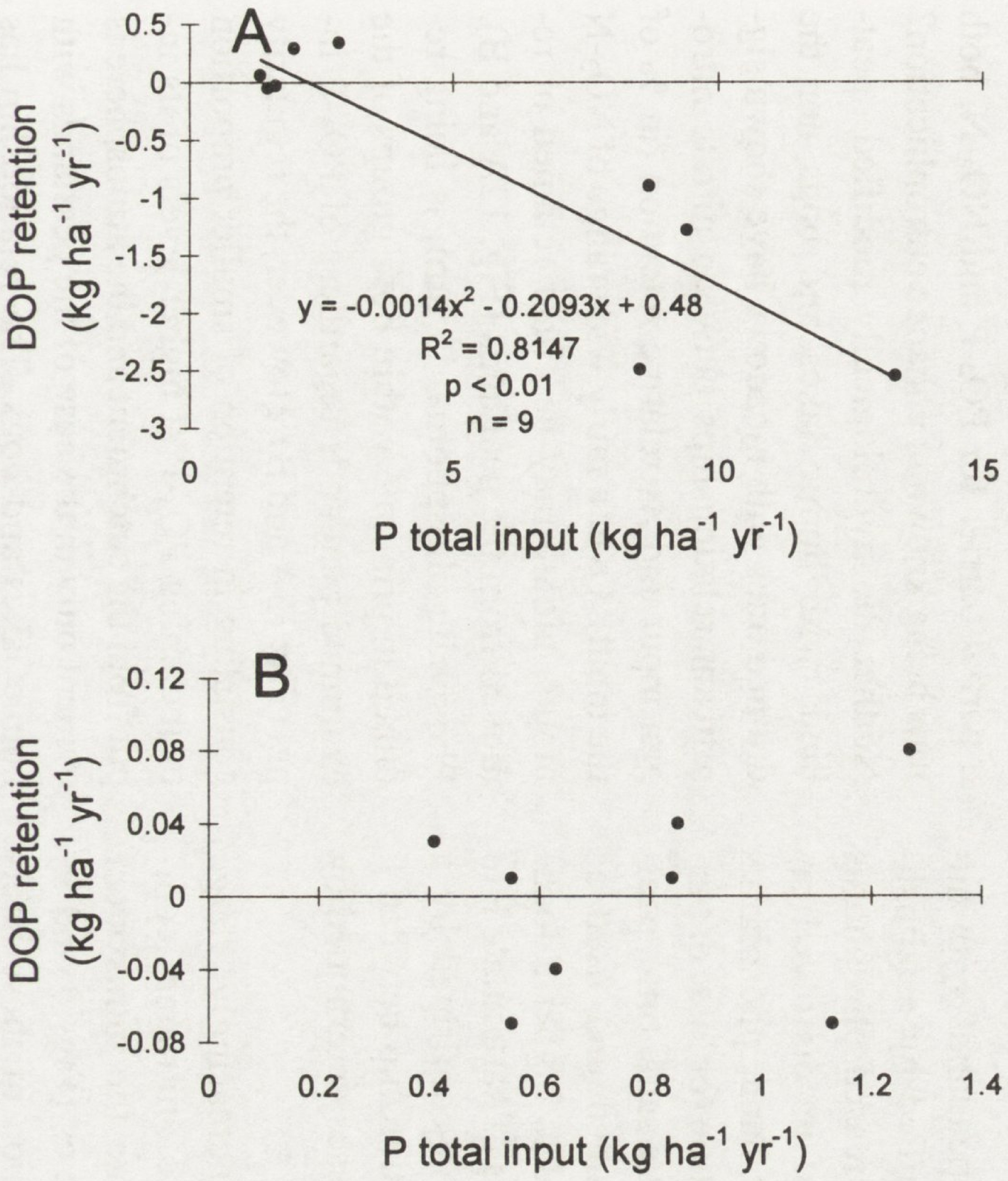

Fig. 10. The effect of total phosphorus input from the catchment and the atmosphere on retention of dissolved organic phosphorus in hydrologically modified peatlands with small humic water bodies and bogs (A) and in drained peatlands with meadows (B). Data: see Fig. 8.

not correlate with the input of total P (Fig. 10B).

Thus, a response of peatlands with humic lakes and bogs modified by establishment of a channel to increased phosphorus supply consists in loss of its dissolved organic form. On the other hand, phosphorus input does not affect retention (or loss) of particulate P (Fig. 11A). At the same time, peatlands that had been drained and used as meadows seem to respond to higher P loads by losing greater quantities of particulate P to outflowing waters. This is confirmed by a significant ($p < 0.01$) relationship between P input and particulate P losses determined by $R^2 = 0.88$ (Fig. 11B).

Incorporation of increasingly large amounts of minerals, i.e. nitrogen compounds and phosphate, into the intrasystem cycling of peatland ecotones (Figs 7 and 9) contributes to eutrophication of these habitats. At the same time, it decreases export of the elements to lakes and rivers. Is this enough to consider the peatlands to be at least a partial barrier for PO_4-P and NO_3-N, both ions being known to enhance eutrophication? Neither the hydrologically modified peatlands with humic lakes and bogs nor the drained ones with meadows have shown significant relationships between nitrate nitrogen input and its relative retention (in % of the input). Over a fairly wide range of NO_3-N inputs, nitrate may be either retained or removed from the peatlands (Fig. 12A and B). Phosphate phosphorus, in turn, is being retained in principle within both groups of the examined peatlands regardless of PO_4-P input (Fig. 13A and B). However, the regularity consisting in retention of smaller proportion of incoming PO_4-P at higher levels of its input from the catchment and the atmosphere is evident only in the case of the peatlands with humic lakes and bogs. The relationship has R^2 equal to 0.74 and is significant at $p < 0.01$.

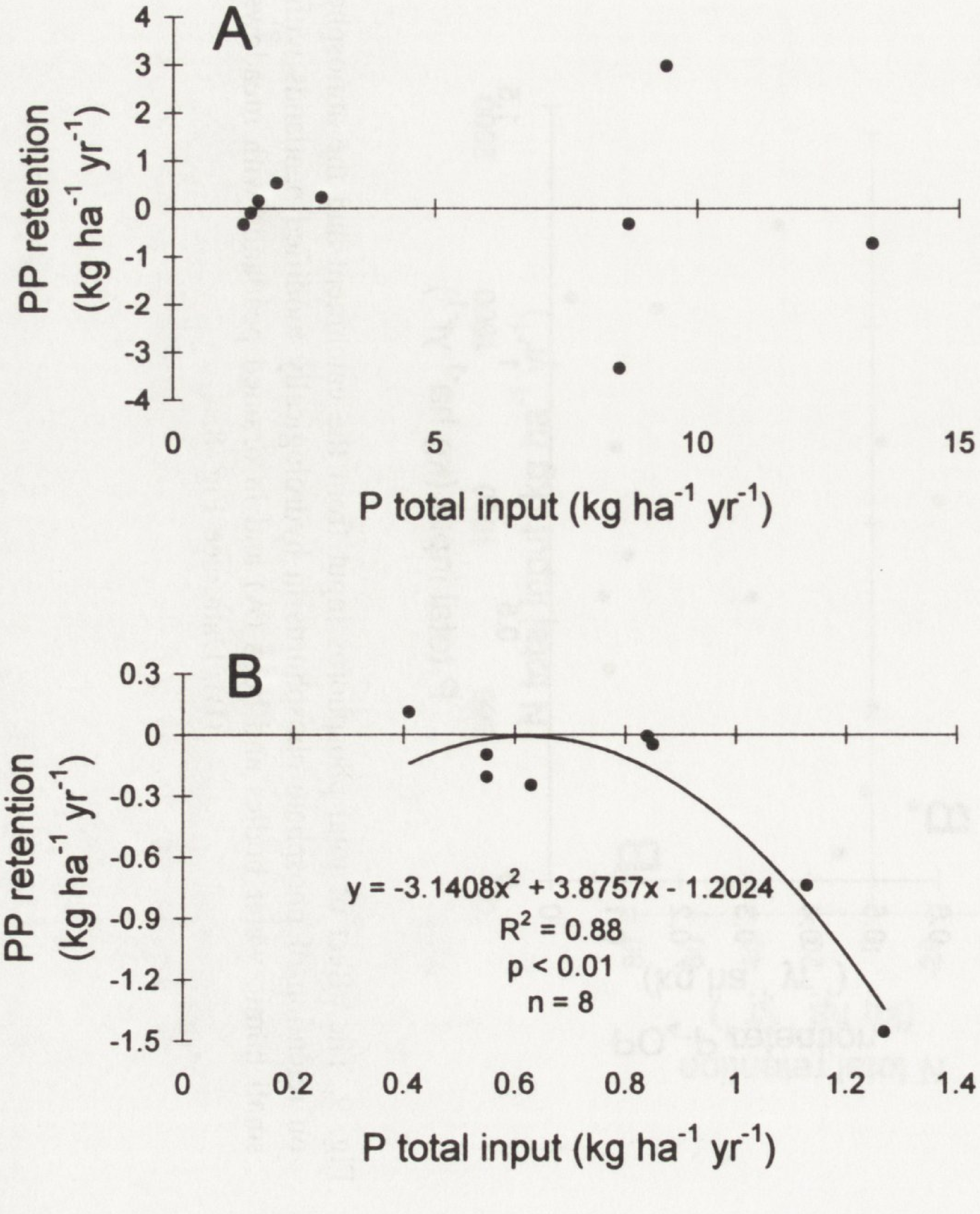

Fig. 11. The effect of total phosphorus input from the catchment and the atmosphere on retention of particulate phosphorus in hydrologically modified peatlands with small humic water bodies and bogs (A) and in drained peatlands with meadows (B). Data: see Fig. 8.

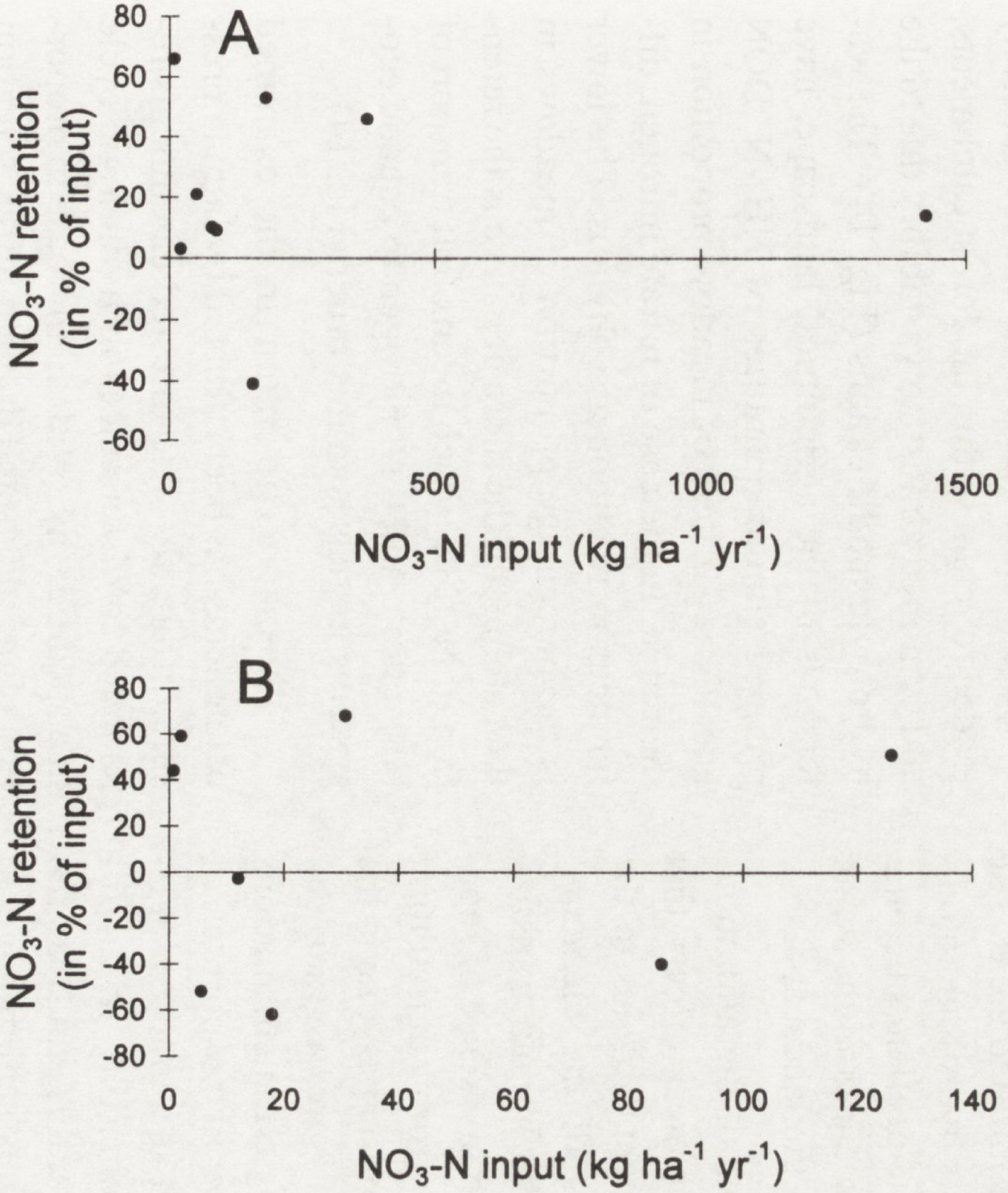

Fig. 12. The effect of nitrate nitrogen input from the catchment and the atmosphere on its retention (in % of input) in hydrologically modified peatlands with small humic water bodies and bogs (A) and in drained peatlands with meadows (B). Data: see Fig. 8.

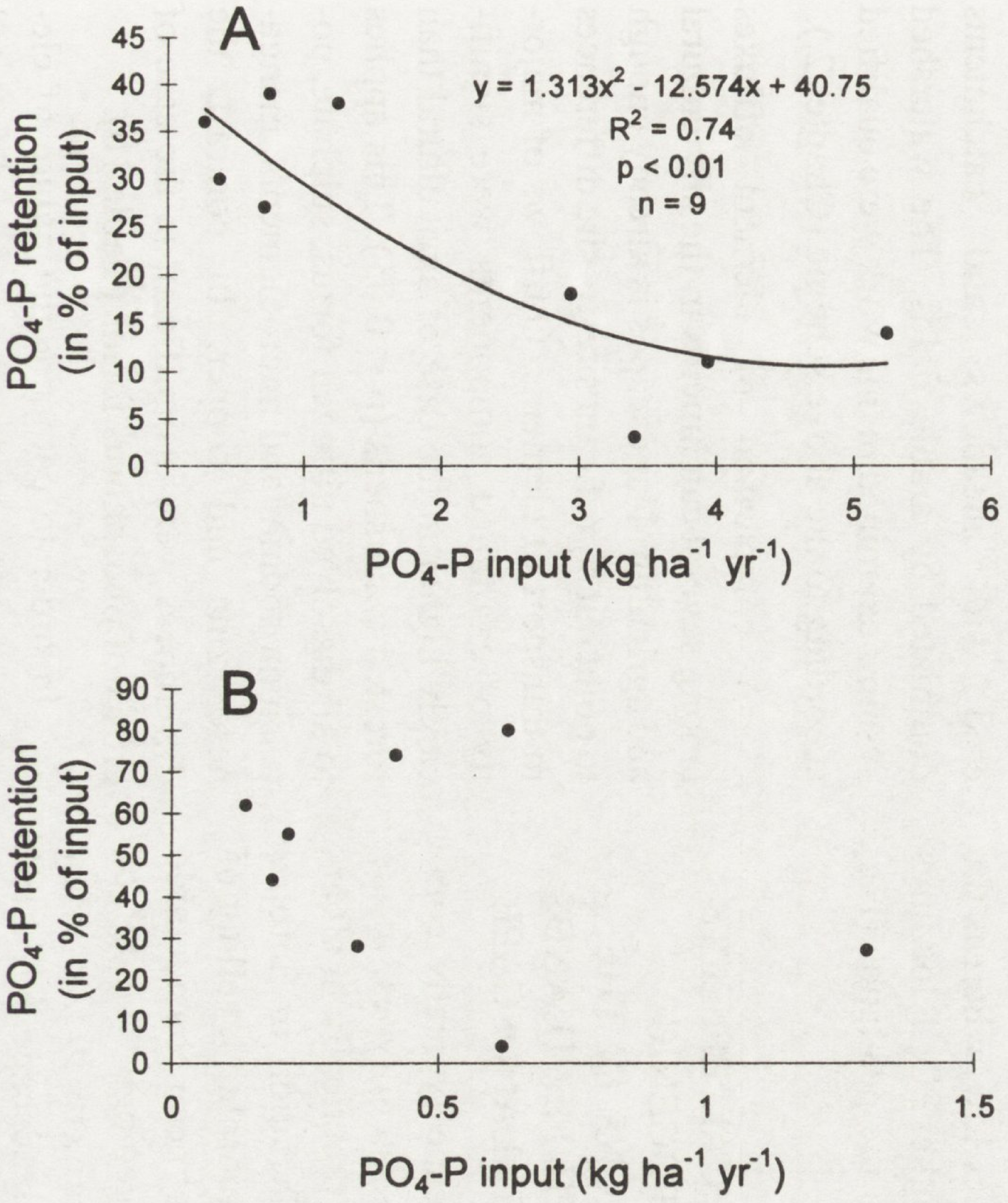

Fig. 13. The effect of phosphate phosphorus input from the catchment and the atmosphere on its retention (in % of input) in hydrologically modified peatlands with small humic water bodies and bogs (A) and in drained peatlands with meadows (B). Data: see Fig. 8.

The modified peatlands with humic lakes and bogs are more effective in retaining phosphate when P-PO_4 input is low, whereas the tendency disappears at higher PO_4-P loadings (above 4 kg ha^{-1} yr^{-1}) to the peatlands (Fig. 13A).

4.6. BIOGEOCHEMICAL EFFECTS OF ANTHROPOGENIC TRANSFORMATIONS IN THE WATERSHEDS WITH PEATLANDS IN THE LAKELAND LANDSCAPE

The lakeland landscape typically comprises fairly diverse ecosystem types. In the Masurian Lakeland, and practically in all areas of the last Baltic glaciation in Europe, natural processes of geomorphic levelling of postglacial relief have not been considerable yet. This is because of geologic "youth" of these terrains (Kondracki 1972). Man transformations of the landscape have led most of all to acceleration of variety of geologic processes such as erosion or lake terrestrialization. The human modifications have principally consisted in deforestation and development of agricultural land use types, as well as in management of forested areas. The activities, to which various hydrologic modifications of catchments and peatlands belong, are associated with disturbances in the water circulation pattern within the landscape.

On a landscape scale, all the alterations have profound biogeochemical effects that consist in adjusting elemental cycles to the man-modified conditions of the elements' transport. To simplify, the human transformations can be considered in a sense of separation of silvicultural from agricultural landscapes. Within the landscapes, due to the overall anthropogenic pressure, a grade can be singled out of hydrologic transformations consisting in an increase in proportion of drained peatlands, as well as a grade of agriculture intensification consisting in an increase in proportion of arable lands at the expense of meadows. Thus, anthropogenic pressure increases in the order: forested catchments with natural mires, catchments with mid-forest meadows, meadow catchments, agricultural catchments partially covered with meadows, and catchments dominated by arable fields. The watershed systems examined in this work were qualified according to the above scheme (Chapter 2.).

A comparison of element effluxes among several catchments in the silvicultural and agricultural landscapes is already enough to point out significant site-to-site differences in transport of elements. Outflows of majority of examined components were significantly higher in the case of agricultural than forested watersheds ($p < 0.05$). This applies to all dissolved nitrogen forms, sulphate, potassium, sodium and microelements: manganese, zinc and copper. In contrast, the differences were insignificant in the case of efflux of phosphorus forms (Table 10).

In order to compare the nature of elemental cycling among the series of forested and agricultural catchments of increasing human pressure, retention of mineral elements (atmospheric input – outflow) was calculated for each of them and drawn schematically on a graph. Nitrogen forms have generally tended to retain within the forest catchments, and exhibited almost no variability due to the hydrologic modifications (Fig. 14). The watersheds of the agricultural landscape, have retained similar quantities of NH_4-N, DON and PN regardless of meadow proportion in their area. In the case of nitrate nitrogen, differences in retention are obvious. The lower is the percentage proportion of meadows in the catchment, the more negative is the retention of NO_3-N, which means that transport of both nitrate and total nitrogen to aquatic ecosystems increases in this order (Fig. 14).

Phosphorus retention in the examined catchments has been affected by human pressure differently. The forested catchments responded to disturbances in hydrologic cycle in a specific way. With an increase in proportion of meadows and drained mires, retention of particulate and total phosphorus has tended toward zero values (Fig. 15). This

Table 10. A comparison of mean (± standard deviation - SD) outflows of mineral elements between typical catchments of silvicultural landscape (forest, forest-mire and forest-meadow) and agricultural catchments (field, meadow and field-meadow). In kg ha^{-1} yr^{-1}.

Element	Measure	PO$_4$-P	DOP	DTP	NH$_4$-N	NO$_3$-N	DON	DTN	SO$_4$-S	Ca	Mg	K	Na	Fe	Mn	Zn	Cu	Pb	Cd
Catchments of silvicultural landscape (n = 7)	mean	0.060	0.048	0.097	0.34	1.53	1.06	2.93	15.3	105.6	9.9	2.81	9.9	0.66	0.068	0.0063	0.0031	0.0004	0.00007
	±SD	0.037	0.033	0.058	0.30	0.69	0.61	0.90	5.9	37.5	3.7	1.63	5.4	0.46	0.037	0.0009	0.0003	0.0001	0.00004
Catchments of agricultural landscape (n = 5)	mean	0.073	0.051	0.124	**0.58***	**5.24***	**2.20***	**13.09***	**46.0***	129.9	16.7	**8.34***	**19.6***	0.58	**0.146***	**0.0091***	**0.0058***	0.0004	0.00008
	±SD	0.011	0.020	0.024	**0.30**	**4.05**	**1.13**	**10.32**	**13.1**	21.6	5.3	**2.93**	**4.0**	0.47	**0.080**	**0.0028**	**0.0019**	0.0002	0.00005

* values significantly higher ($p < 0.05$), typed with bold font.

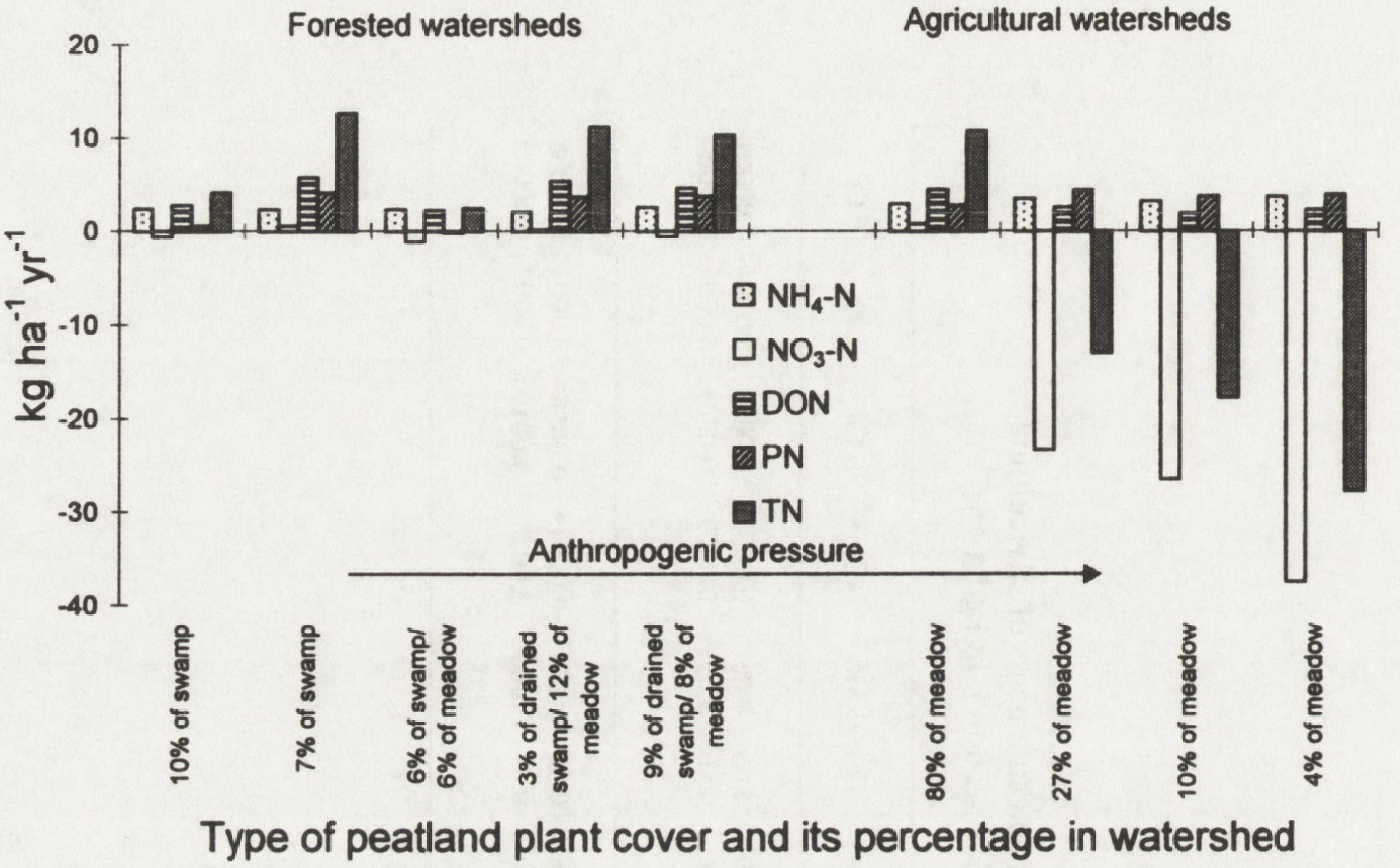

Fig. 14. Nitrogen retention (atmospheric input - outflow from the catchment) in forested and agricultural watersheds of different modification degree of peatlands and different acreage proportion in the order of increasing anthropogenic pressure in the lakeland landscape.

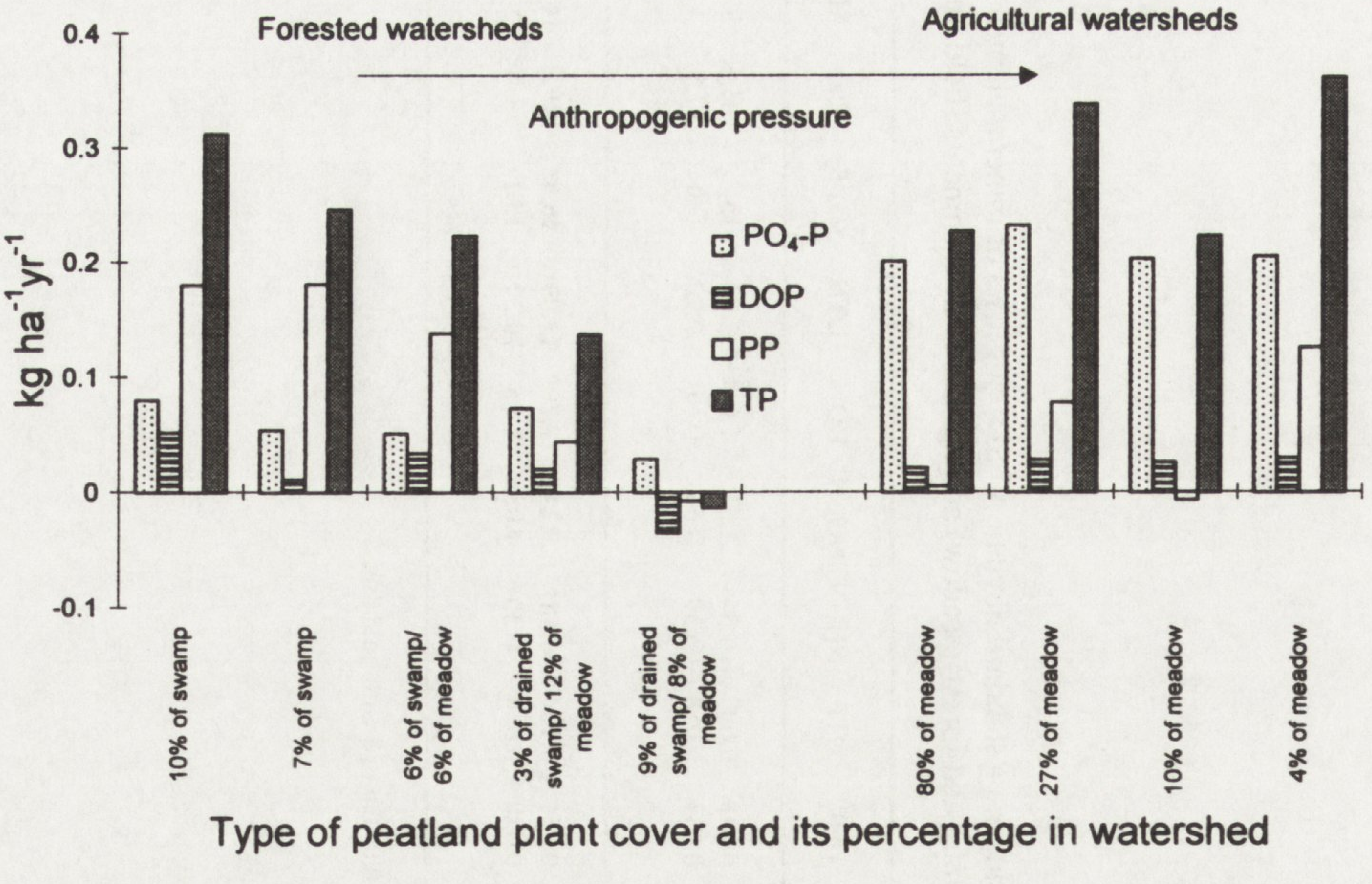

Fig. 15. Phosphorus retention (atmospheric input – outflow from the catchment) in forested and agricultural watersheds of different modification degree of peatlands and different acreage proportion in the order of increasing anthropogenic pressure in the lakeland landscape.

means that the tendency to retain P is being weakened and therefore lakes and rivers are at risk of enhanced eutrophication, despite consistently retention of PO$_4$-P. It is noteworthy that substantially larger amounts of phosphate have been retained in the agricultural than forested catchments. Phosphorus retention has not decreased with increasing intensity of land use in the agricultural watersheds (Fig. 15).

The effect of agricultural use is evident in the case of sulphate sulphur retention within the watersheds. In the forest landscape, SO$_4$-S retention was moderately negative, whereas in the agricultural areas substantial losses of the element were ob-

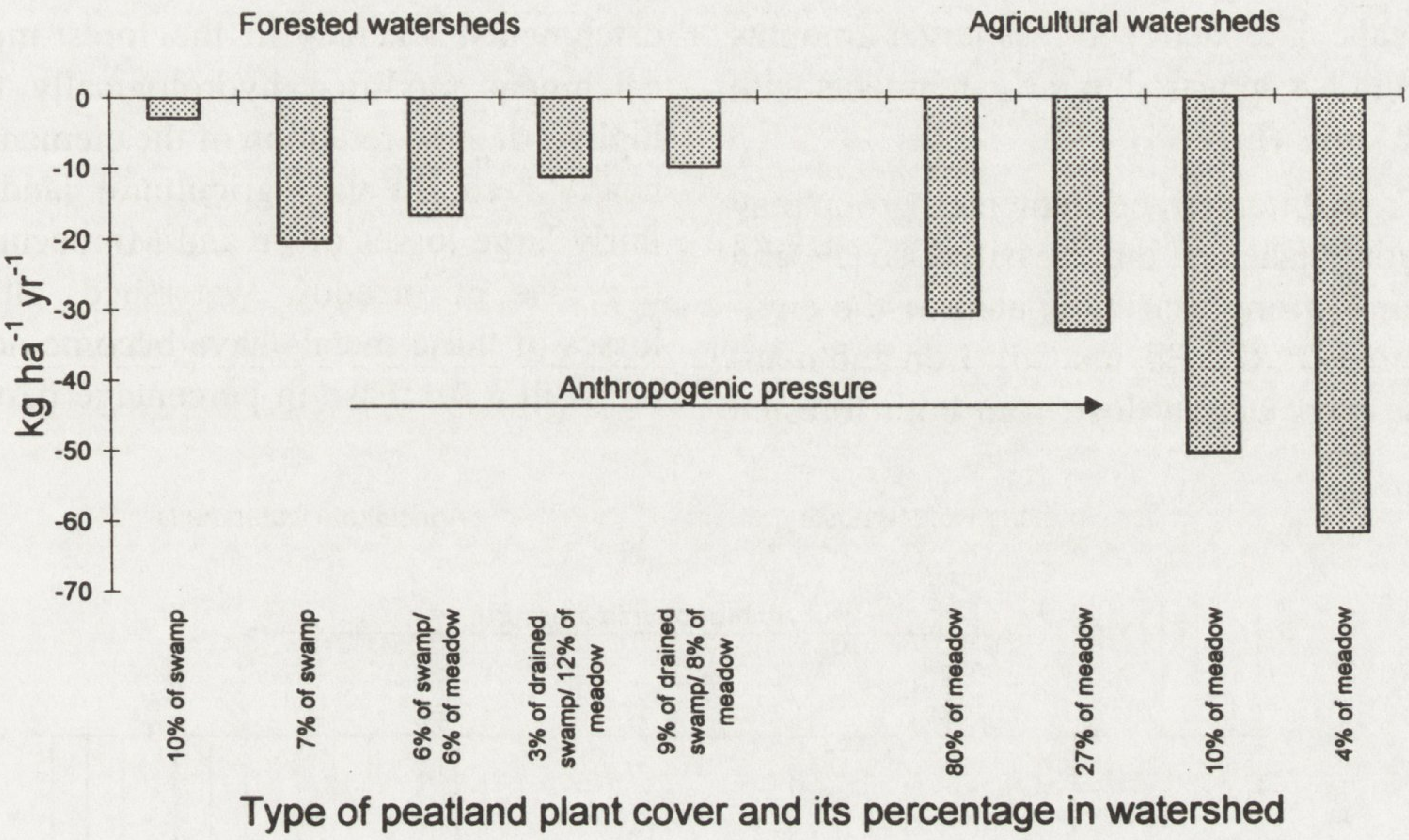

Fig. 16. Sulphate sulphur retention (atmospheric input – outflow from the catchment) in forested and agricultural watersheds of different modification degree of peatlands and different acreage proportion in the order of increasing anthropogenic pressure in the lakeland landscape.

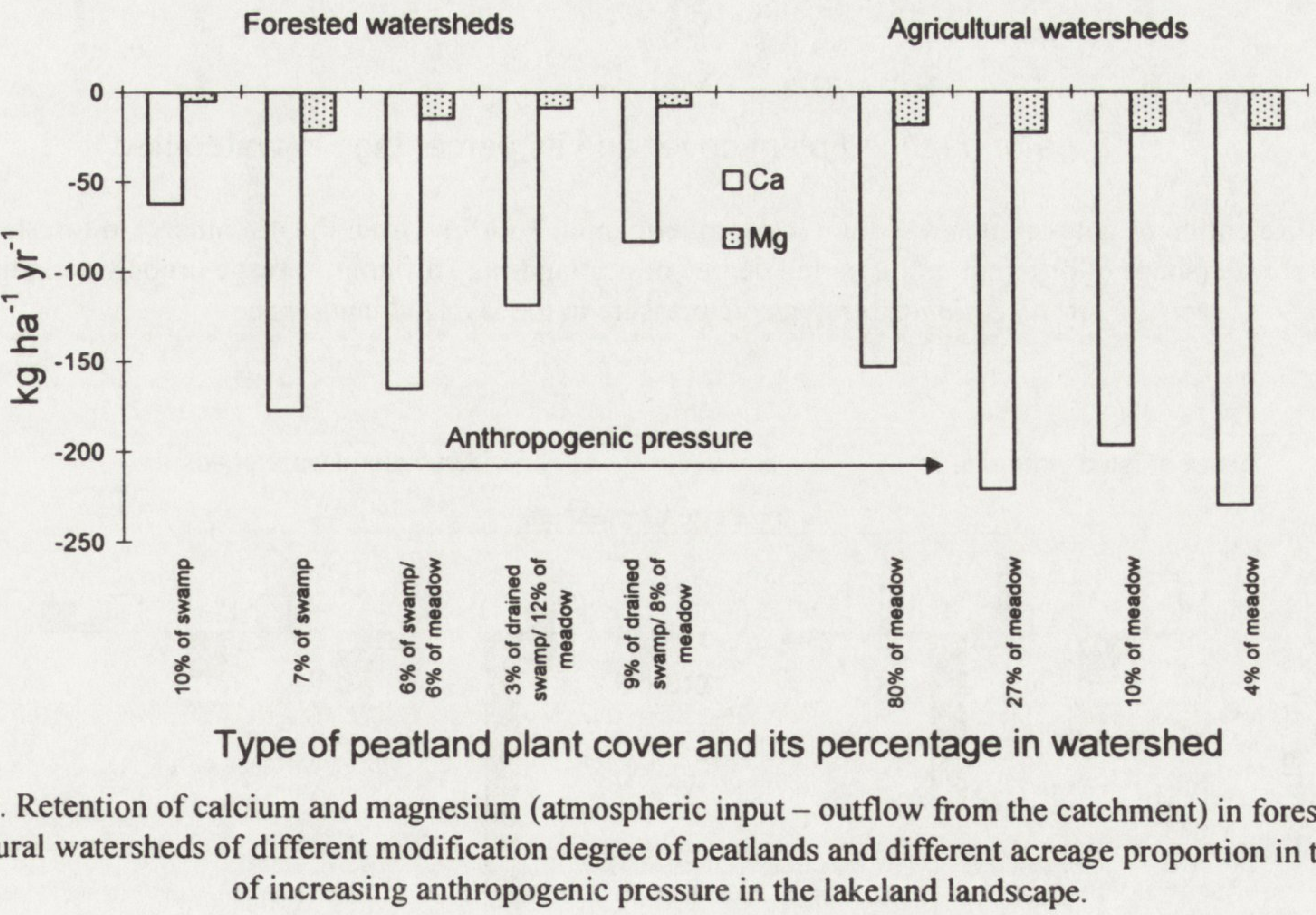

Fig. 17. Retention of calcium and magnesium (atmospheric input – outflow from the catchment) in forested and agricultural watersheds of different modification degree of peatlands and different acreage proportion in the order of increasing anthropogenic pressure in the lakeland landscape.

served. In addition, SO_4-S loss increased along with increasing proportion of arable lands in the catchment area (Fig. 16). Retention of calcium and magnesium in the forest landscape was negative, although fairly variable, whereas in the agricultural landscape it was consistently negative and thus indicated intensive leaching of both elements. Slightly smaller quantities of the metals have been lost from the meadow watershed (Fig. 17). Retention of potassium and sodium in the forest catchments was highly variable. The catchments may lose as well as retain small quantities of the elements. In the agricultural landscape, a tendency to loss larger amounts of K and Na appeared in the catchments with arable lands (Fig. 18).

From among trace elements a group may be distinguished of those easily lose (Fe and Mn) and strongly accumulated in the environment (Zn, Cu, Pb and Cd). Iron and manganese were clearly lost from both forested catchments, whereas in the forest-meadow catchment modified hydrologically to the highest degree, retention of the elements was nearly zero. In the agricultural landscape, fairly large losses of Fe and Mn occurred in the case of meadow watershed, although losses of these metals have become negligible with a decrease in percentage participa-

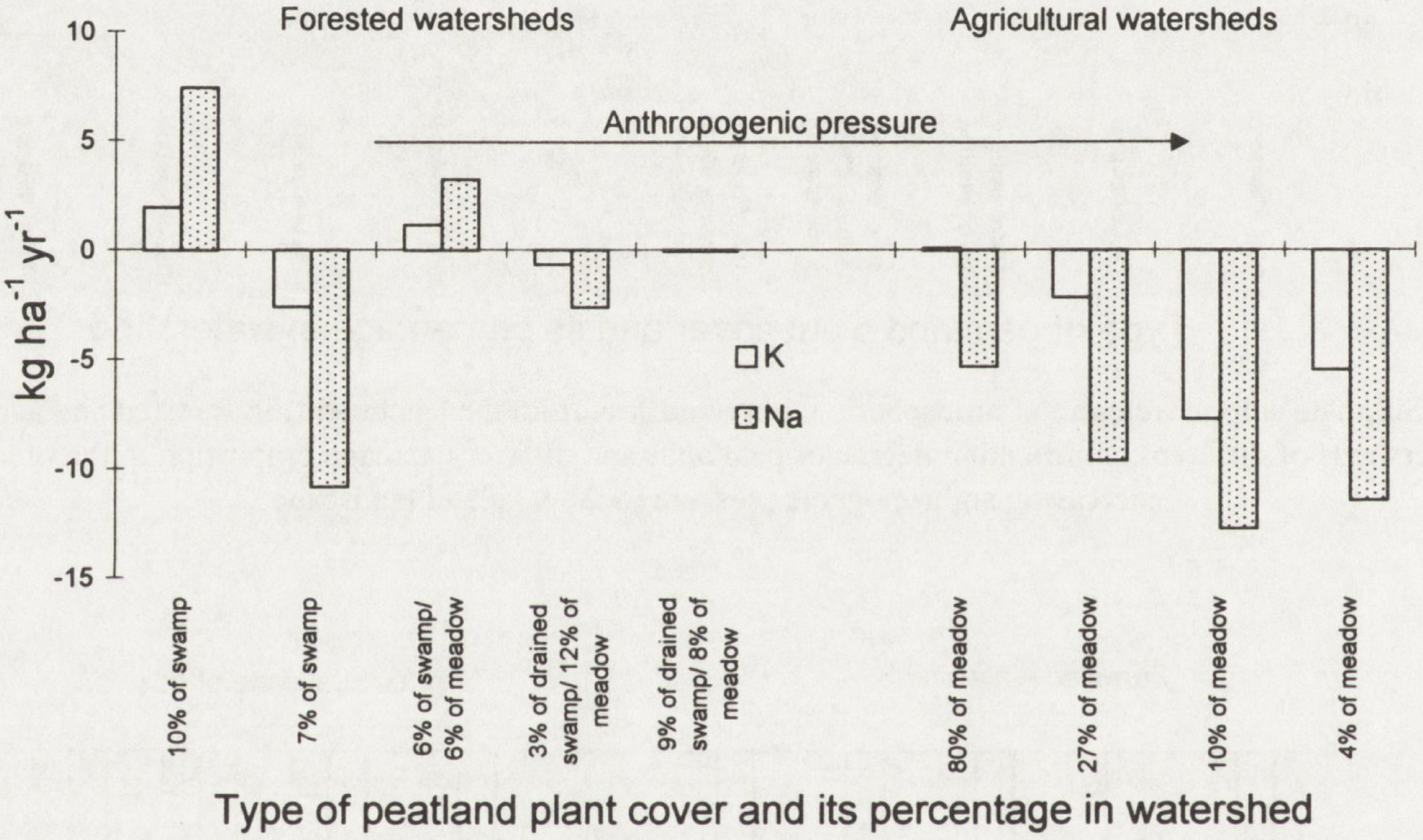

Fig. 18. Retention of potassium and sodium (atmospheric input - outflow from the catchment) in forested and agricultural watersheds of different modification degree of peatlands and different acreage proportion in the order of increasing anthropogenic pressure in the lakeland landscape.

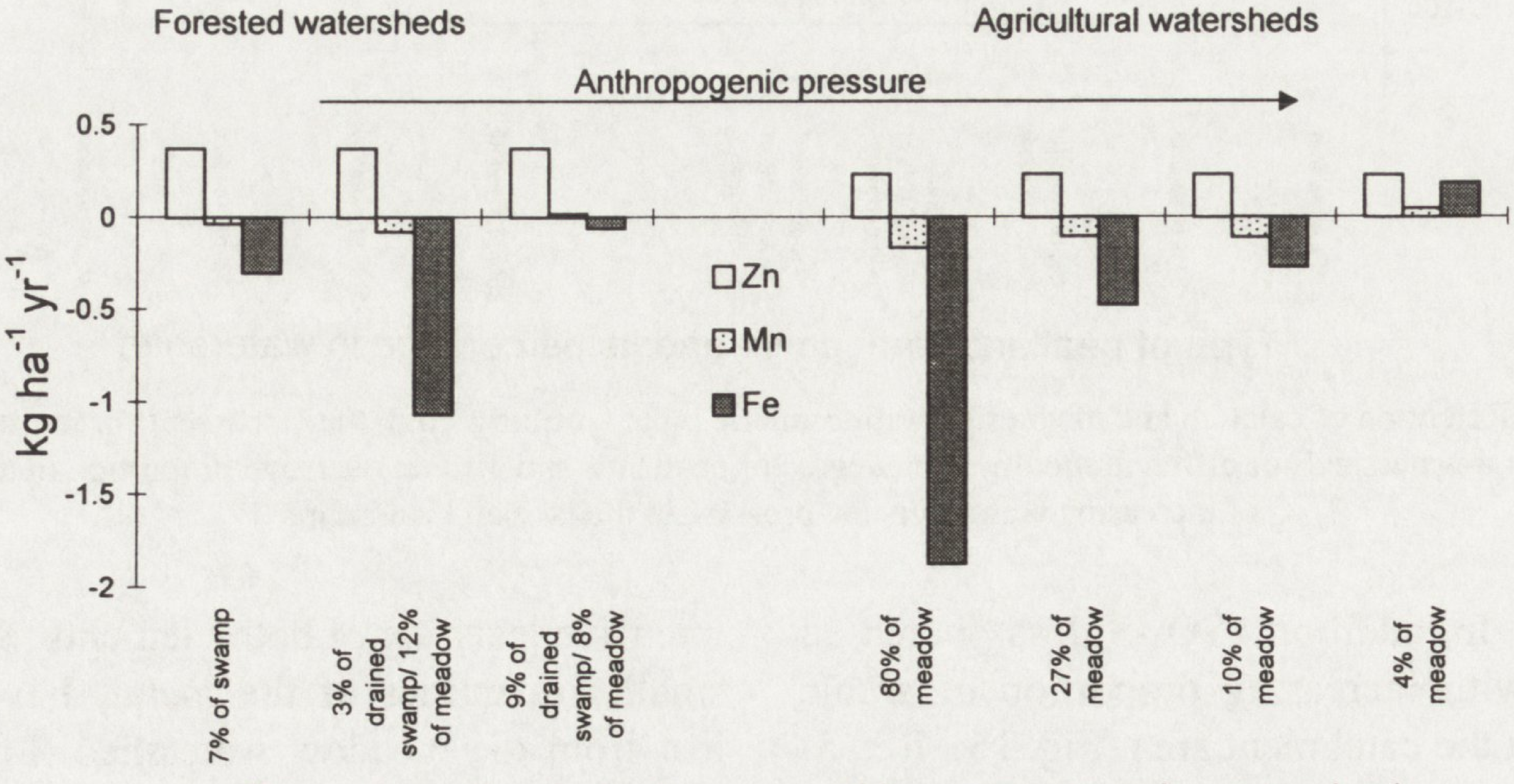

Fig. 19. Retention of zinc, manganese and iron (atmospheric input – outflow from the catchment) in forested and agricultural watersheds of different modification degree of peatlands and different acreage proportion in the order of increasing anthropogenic pressure in the lakeland landscape.

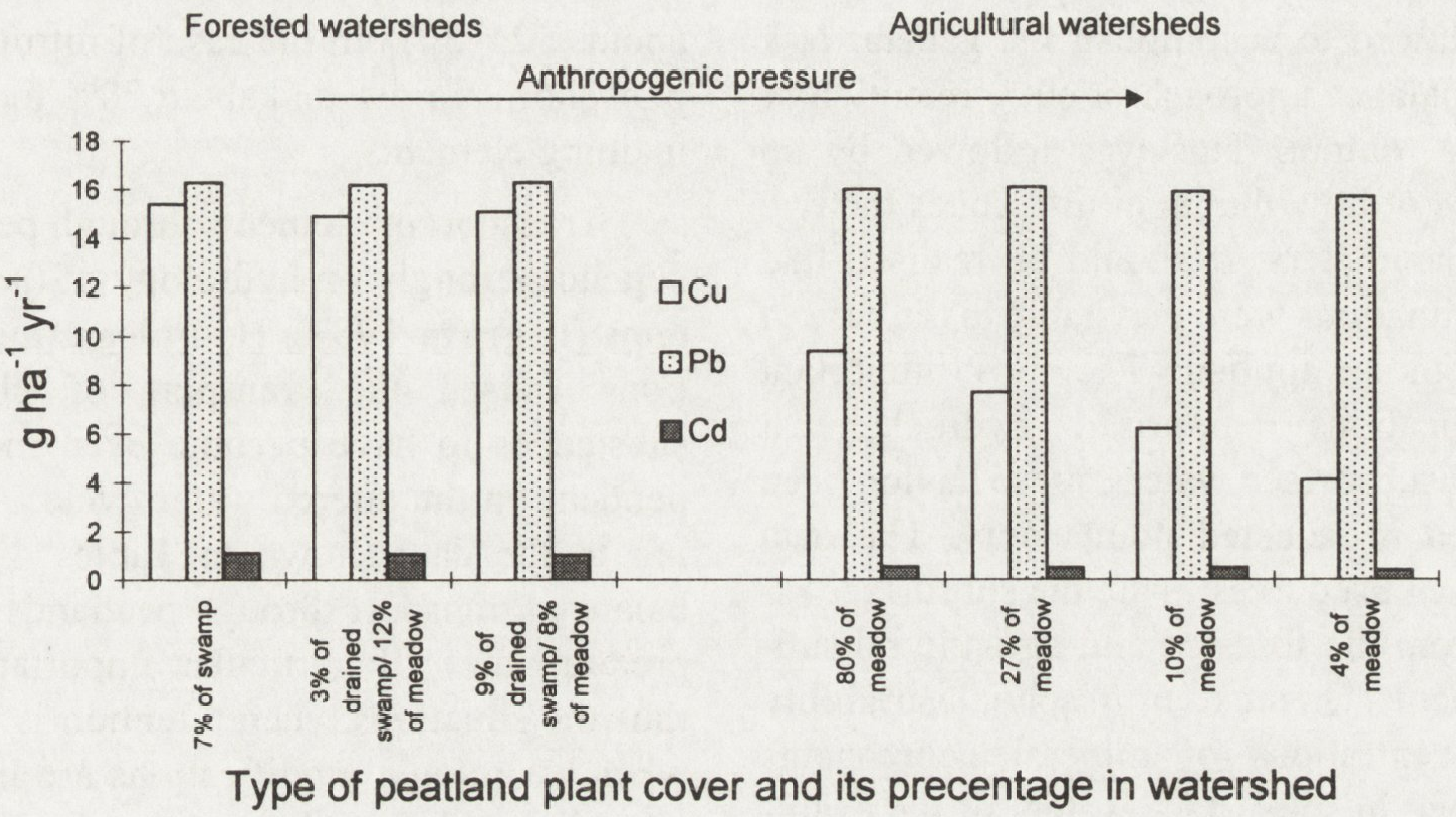

Fig. 20. Retention of copper, lead and cadmium (atmospheric input – outflow from the catchment) in forested and agricultural watersheds of different modification degree of peatlands and different acreage proportion in the order of increasing anthropogenic pressure in the lakeland landscape.

tion of meadow area in the catchment. In this case, we deal with a fairly clear gradient (Fig. 19). Although zinc has consistently accumulated in watersheds of both types, forest systems retained slightly larger amounts of the element (Fig. 19). Forest and agricultural landscape differ markedly with regard to copper retention within the watersheds. Copper has been tightly retained in the forested catchments, whereas in the agricultural areas its accumulation was about two times smaller and a gradual decrease in Cu accumulation took place with decreasing proportion of meadows in the catchment area (Fig. 20). Lead and cadmium have accumulated at similar levels in all catchments, although Cd retention was slightly lower in the agricultural landscape (Fig. 20).

5. DISCUSSION

5.1. THE EFFECT OF HYDROLOGICAL MODIFICATIONS OF PEATLANDS ON TRANSPORT OF ELEMENTS

Peatlands as being ecotones between areas of higher elevations and water bodies (rivers and lakes) are typical components of lakeland landscape. Under natural conditions the systems have a successional tendency to terestrialization, and thus to lose their transitional character between land areas and waters (Moore and Bellamy 1974). This natural process is associated with overgrowing and succession of lakes and transformation of the whole young postglacial landscape towards more plain relief (Marks 1992). On a short time scale, co-occurrence of morains, peatlands and lakes is conducive to harmonious transformations of the landscape and adjustments of existing biocenoses to the changes. This is worth realising with respect to anthropogenic transformations of the landscape. There is a body of evidence that, beside deforestation, it is transformation of wetlands that has the most deleterious effect on the lakeland landscape. Hydrologic modifications constitute a basis for wetland use as e.g. green crops, forest drainage areas or as a tool for regulation of lake waters. Biogeochemical description of the man-modified natural systems as ecotones between lands and water bodies was the main objective of this work.

The primary methodological assumption that allowed to accomplish the general task was a balance approach: input – retention or losses – output. This was followed by an analysis of how the input influences the two latter parameters. It should be realised that approximations were inevitable in the case of the methods applied. The most important simplifications comprised hydrochemical data on subsurface waters, these having been gathered in selected points only. The data were then used to estimate the subsurface inflow from the forested and agricultural subcatchments. On the basis of spatial variability in concentrations of mineral components contained in subsurface waters of the examined area it can be assumed that measurement errors ranged between 25 and 30% for N and K and between 10 and 18% for sulphate and metals, respectively (Kruk 1990). Differences in the volume of water flow through the agricultural lands, as well as in NH_4-N and PO_4-P loads discharged from the agricultural watersheds in drains during short periods (1–2 weeks) may be considerable, exceeding even 30% (Borowiec and Zabłocki 1981). Inaccuracy in estimates of elemental budgets should also be expected in the case of atmospheric input sampling. For technical reasons, rainwater collectors were placed in a distance from the examined sites, though within the same forest or agricultural area. Furthermore, despite preservations, atmospheric input of organic and particulate nitrogen could be underestimated due to possible N mineralization and losses to the atmosphere. This is a common phenomenon occurring as a consequence of inseparation of the dissolved forms from the dust fractions of precipitation (Dillon et al. 1988). Moreover, tree canopies can intercept an additional pool of nitrogen derived from horizontal input of aerosols (Kwiecień 1988). Inseparation of wet and dry deposition is the most likely reason of a fairly high value of precipitation pH. The pH value found in this study corresponds with those obtained previously in the study area by Kufel (1996). Generally, a reasonable range of the estimate error for elemental budgets is about ± 25–30% in the case of nitrogen and phosphorus forms and about 20% for the remaining elements.

Transport of elements through peatlands depends strongly on hydrology of these systems (Ingram 1983). Hydrologic modifications caused the transport of chemical substances to have become even more dependent on the altered water cycle. According to the data shown in Tables 4 and 5, balanced transport through peatlands clearly predominate. Of particular importance are thus the situations when retention is high or when hydrologic modifications are likely to alter the natural tendency to retain elements towards more balanced transport or even losses of the elements from the peatlands. Such situations occurred in all the examined peatland types.

Natural humic (dystrophic) lakes mostly occur where water flow is limited or adjacent land supplies its with acidic waters. It is accepted that these are conditions which determine chemical properties (acidity) of the lakes and their succession towards ombrotrophic bogs (Stangenberg 1936, Moore and Bellamy 1974, Kratz and DeWitt 1986). Matter flux occurs through water exchange between a system water body, peat moss mat and the peatland and the surroundings formed from mineral substrate. This consists in levelling water tables of the components, as they are diversified due to local differences, primarily those in evapotranspiration (Hooper and Morris 1982). These processes are not intensive.

The influence of man activity on these specific ecosystems is particularly evident in the case of two types of measures. The first one comprises hydrologic modifications induced by e.g. forest drainage and consisting in connecting a lake to a larger drainage area, as is the case of investigated systems. The second one consists in liming in order to increase pH for fishery purposes (Blomqvist et al. 1995, Lampert and Sommer 1996) or to counteract enhanced acidification brought about by "acid rain" and leading to mobilisation of toxic Al (Nyberg and Thörnelöf 1988, Olem 1991, Henricksen et al. 1995). Environmental effects of both measures are similar and comprise increases in pH of open water areas above 7 (Górniak 1996) and changes in peatland vegetation, consisting principally in disappearance of peat mosses *Sphagnum* sp., these being very sensitive to raised pH (Glaser et al. 1990, Zdanowski and Hutorowicz 1998). An ecosystem of a humic lake subjected to liming has undergone long-term transformations, although its nutritional status may be maintained at a fairly low level. On the other hand, as decomposition of organic matter is being accelerated, the water body becomes endangered by eutrophication (Hillbricht-Ilkowska et al. 1998).

When the volume of water flow in dystrophic lakes increases, sedimentation of amorphous oxides of Fe and Al complexed with phosphorus stops functioning effectively, while flux of phosphorus bound to clay minerals and apatite derived from the catchment begins to play an increasingly important role (Jonsson 1997). Also iron discontinues to be sedimented, and in periods of intensive throughflows (snow melt) it may be even rapidly hydrologically moved out. Under such conditions, sediments of the lake are no longer a trap for phosphorus (Boström et al. 1982), and contrary to this, the element is being hydrologically moved out mostly in organic and to a lesser extent in particulate forms. In formerly dystrophic lakes where biogeochemical systems became "open" through channelling of the area, organic sediments, containing even about 70% of the total phosphorus pool of the lake (Rzepecki 1997), have been washed out. Several dozen years of man activity modifying the hydrological systems have led to mobilisation of P pool that has accumulated in the lake sediments for several thousand years.

Symptomatic is a comparison of P and Fe retention between the peatland with humic lake examined in this work and a dystrophic lake with a natural watercourse in the southern Finland. About a half of both elements has accumulated in the lake of the latter site (in period May – September), which is typical of dystrophic lakes. However, inflow of Fe was a few times higher, and that of Ca – a few times lower here (Arvola et al. 1990) when compare with the lakes of the Masurian Lakeland. Thereby, not only water flow through a dystrophic lake alone, but also chemical properties of inflowing waters resulting from mineral composition of the catchment bedrock, such as rich in Ca resources in the Masurian Lakeland, may change the nature of the humic lake.

In the course of natural evolution of boreal and sub-boreal peatlands, this phase of land-forming process in a relic humic lake is followed by a stage without surface water area. The water body becomes completely overgrown with a mat of peat mosses *Sphagnum* sp. and plant communities typical of transitional peatlands belonging to the order *Scheuchzerietalia palustris* Nordh. 1937 or occured in various successional series of *Caricetum rostratae* Rübel 1912 association (Matuszkiewicz 1981). This is the stage of transformations leading towards typically ombrophilous peatlands with bog coniferous forests (Wilpiszewska 1990). An apparent symptom of eutrophication of the examined system incised with a watercourse is among other expansion of eutrophic community with common reed *Phragmites australis* and scented fern *Dryopteris thelypteris* (Kruk 1997c). This is because the natural bog vegetation is very susceptible to water eutrophication (Glaser et al. 1990, Bragg and Clymo 1995).

Peatlands with bogs are considered as systems effectively retaining matter in a form of peat. According to Bazilevich and Tishkow (1982), about 8% of energy flux through a mesotrophic bog system is being excluded and accumulates in organic sediments. This feature combined with topographic isolation cause the peatlands with bogs to be capable of retaining mineral components derived mainly from the atmosphere. This is indicated by elemental balances for various undrained peatlands with raised bogs (Table 11). Retention of majority components exceeded a third part of their inputs. Lead, sulphate sulphur and calcium were most (50%), whereas potassium – least strongly retained elements. Heavy metals incoming from the atmosphere are especially tightly retained by peat mosses (Lee and Tallis 1973, Pakarinen 1978). It should be mentioned, that a bog surrounded by agricultural areas and receiving an additional load of elements from its fertilised catchment accumulates a higher percentage of elements than peatlands in less modified catchments. In mid-field bogs it may lead to broadening of the fertile edge zone (lagg) and eventually to disappearance of the bog biocenosis (Kruk and Podbielska 1998). In contrast, channelled peatlands with bogs lose their capacity of retaining most elements. Except less effectively retained nitrogen, only lead and sulphate sulphur display more evident retention, whereas other metals are being moved out from the peatland catchment or their throughflows are nearly balanced (Table 11).

Biogeochemical functioning of the peatland with transitional bog examined in this work is characterised by fairly regular cycles of retention and losses of mineral components (Kruk 1997b). It turns out that factors determining retention or losses of the elements differ between the growing and dormant season (Table 7). To simplify, retention of N, P and S in spring and summer periods is connected with inputs of these elements from the catchment and the atmosphere, which indicates strong plant accumulation. Additionally, mobilisation and biotic retention of phosphate may be affected by increased inflow of easily assimilable nitrate ions, due to channeling the peatland. Probably, nitrate production could be limited before channelling of the area due to typically low nitrification rates in acidic bog environment (Waughman 1980, Etherington 1983). Moreover, enhanced retention of phosphate resulting from the increase in atmospheric input of hydrogen is likely to be brought about by geochemical reasons. At pH lower than 5.7, a tendency to bind phosphate by minerals containing Fe and Al increases (Stumm and Morgan 1970, Lindsay 1979). This phosphorus pool is not however stabile and may be mobilised under anaerobic conditions.

Leaching of major cations from moss peat deposits has been recognised (Malmer 1988), which can be intensified by higher at-

Table 11. Element retention in % of the element inputs in peatlands with bog of unchanged and changed by watercourse hydrologic system. nd – not detrmined.

Peatland hydrology	N	SO_4-S	Ca	Mg	K	Na	Pb	Source
Non-modified	37[a]	77	nd	45	–25	nd	98	Hemond (1980)
	nd	nd	50	22	21	44	nd	Urban et al. (1995)
	86	97	79	80	21	74	nd	Kruk (1990)[b]
Modified by a watercourse	45	16	–154	–112	-96	-61	nd	Lundin and Bergquist (1990)[c]
	17	28	3	7	11	6	44	Kruk (this work)

[a] NO_3-N + NH_4-N

[b] bog in agricultural surroundings

[c] recalculated

mospheric loads of e.g. NO_3-N, a component of "acid rains" (Skiba et al. 1989, Sanger et al. 1996). During the dormant season (November – April) only phosphorus retention depends on nitrate input. A characteristic feature of this period is that all components, except nitrogen forms and manganese, retain in the peatland, which relates to periodical increase in water storage.

It is also showed that NO_3-N retention increases as affected by sulphate input from the atmosphere. It is not unlikely, that increased sulphate input as an effect of "acid rains" influences microbiological immobilisation of incoming nitrate in active layer ("acrotelm") of ombrotrophic peatlands (Sanger et al. 1996). It is to add, that ionic interactions in the system: input – vegetation – moss peat have not been fully recognised yet. In general, larger quantities of nitrate appearing in stream waters that feed the bog peatland disturb relations between this and other ions, mostly with NH_4-N, the ion being a dominant mineral form of nitrogen in acidic peatland waters (Damman 1988, Kloss 1993) and, at the same time, the ion preferred by the specific bog vegetation (Urban and Eisenreich 1988, Hayati and Proctor 1991).

It seems that the main process leading to over-eutrophication of bog peatlands affected by hydrologic modifications is following. Nitrate ions limited under typically ombrotrophic conditions are, after enrichment of their pool by stream waters, intercepted by expansive species typical of eutrophic environments (e.g. by common reed) and characterised by higher productivity, but lowered use efficiency of nutrients resources (Bridgham et al. 1995). This accelerates intrasystem nitrogen cycling, the process occurring slowly under ombrotrophic conditions. Thus, nitrate that infiltrates from stream waters to the active peat layer can be regarded, besides phosphate retention stimulated by input of this ion, as a driving force of accelerated N and P cycling and progressive eutrophication of the bog habitat. Additionally, supply of mineral components available to plants during the growing season increases as influenced by former rise of water storage in winter and early spring. As being a typical feedback effect, eutrophication of bog peatlands increases their productivity, which in turn, alters hydrologic relations in the peatland leading to acceleration of successional changes (Logofet and Alexandrov 1984).

Although the peatlands with relic humic lakes and transitional bogs were exposed to hydrologic modifications, they have still remained mires with permanent water bodies, with continuously flooded parts and with plant communities in the transformation phase, which provides peat-forming processes to continue. The range of hydrologic modifications examined in this work comprises also those more radical ones, namely peatland drainage and transformation of its natural vegetation cover into less or more intensively cultivated meadow communities. From the standpoint of matter cycling in the landscape, these commonly occurring systems characteristically gain an additional pool of elements with fertilisers, and lose an extra pool in grass yield harvesting. This anthropogenic cycle may disturb natural matter flux within the system: the atmosphere – hydrologic outflow. In the case of studied peatlands with meadows, influence of such measures was rather limited. Both meadows were at most extensively used, and the main difference between them, besides surroundings, consisted in the depth of drainage. The meadow in the agricultural catchment had a system of deep ditches and drains.

Differences in yearly net retention of mineral components between the examined meadows are not considerable. The retention of NH_4-N and PO_4-P and distinct leaching of Ca and Mg occured in the drained peatland in the agricultural surroundings but these processes did not occur in the mid-forest meadow. Positive balances of ammonium might be an effect of its conversion into nitrate. Thus, nitrification processes lead to decrease pH of groundwater and induce ionic exchange in the rot-peat soil, which leads eventually to displacement of calcium and magnesium ions from exchange sites, as well as to losses of NO_3-N (Zimka and Stachurski 1996). Positive balance of ammonium obtained in this work may mask also two alternately occurring processes: volatilisation of NH_3 from the soil, detritus and fertilisers (Steele 1987) or retention of NH_4-N derived from the atmosphere, especially when temporary shortages of the ion in the soil occur (Harper et al. 1983).

Another process possibly affecting nitrogen budget in the ecosystems of peatland meadows is denitrification (Knowles 1981, Martikainen et al. 1993, Koops et al. 1997). Because nitrogen cycle within these systems depends on a variety of factors connected with land use and environmental conditions (Steele 1987), nitrogen balances may vary considerably among particular drained peatlands. Retention of PO_4-P may be, in turn, attributed to phosphate assimilation by grasses and their export outside the system, although the nutrient may also be immobilised in colloidal particles and Fe and Al complexes present in the rot-peat soils (Velayutham 1980, De Mars et al. 1996).

The studies have confirmed opinions of other authors that meadow ecosystems formed on organic soils and developed as an effect of peatland drainage are characterised by a tendency to lose or to have at most balanced throughflows of macroelements. This is a consequence of altered moisture conditions, which results in enhanced mineralization of nitrogen and sulphur (Lee et al. 1975, Dowding 1981, Grootjans et al. 1985, Gotkiewicz 1991, Kruk 1997a), leaching of particulate phosphorus (Crisp 1966, Burwell et al. 1975) and cations, particularly calcium and magnesium (Crisp 1966, Zimka and Stachurski 1996, Piaścik et al. 1997). The drained peatlands are usually an effective source of such metals as iron and manganese and, at the same time, they are biogeochemical barriers for heavy metals (dissolved forms of Zn, Cu, Pb and Cd). Presumably, the metals, except copper, accumulate in meadow ecosystems even when their transport as organic complexes is taken into an account (Życzyńska-Bałoniak et al. 1993).

The agricultural landscape in lakeland areas comprises not only arable fields, pastures or meadows, but also wetlands associated with depressions with no outflow, the latter ones being ecotones between the agricultural catchments and subsurface outflow to lakes and rivers (Kloss and Wilpiszewska 1985, Kruk 1987, 1990, Wilpiszewska 1990, Kloss 1993, Kruk 1996). Some of them are undrained peatlands, the biocenoses of which are however considerably deformed as being influenced by the agricultural surroundings. In context of this analysis, these mid-field mire systems constitute a transitional stage of transformations of peatland ecosystems in the present-day landscape, namely the phase following deforestation without subsequent drainage of the peatland.

It appears that undrained mid-field peatlands receiving sometimes even very high loads of minerals from the fertilised catchments are not able to inhibit throughflows of the mineral components. This applies to e.g. phosphate, the ion having been additionally displaced from deposits probably by a considerably large loadings of sulphate derived from fertilisers (Kruk 1996). Nitrogen is an exception, because it is efficiently intercepted mostly as nitrate (Kruk 1997a). Besides PO_4-P, the peatlands may be a source of potassium (Table 12). After drainage, the systems lose their capability of retaining N and start to move out sulphur resources. Long-term drainage and peatland use as meadows do not restore the tendency to retain nitrogen, transport of phosphorus and sulphur is balanced, whereas calcium and magnesium tend to be lost from the peatlands. To compare, a drained upland peatland with blanket bog used as pasture in England has much higher indices of element loses (Table 12). Thus, when a peatland loses its water storage

Table 12. Element retention in % of the element inputs in the peatlands in agricultural areas: undrained, immediately after drainage (first year) and drained a longer time ago and managed as meadows and pasture; nd – not determined.

Peatland	N	P	SO_4-S	Ca	Mg	K	Na	Source
Undrained	73	–55[a]	17	19	17	–186	28	Kruk 1990, 1996
Immediately after drainage	0	nd	–232	–7	9	57	1	Kruk 1990
Drained a longer time ago (meadow)	12	8	6	–39	–50	10	–5	Kruk (this work)
Drained a longer time ago (pasture)	–116	–22	nd	–553	nd	–260	–77	Crisp (1966)

[a] PO_4-P

capacity due to drainage, elements accumulated in the period of wetland functioning and sedimentation of organic matter usually begin to be leached.

5.2. PEATLAND ROLE IN WATER EUTROPHICATION AND BIOGEOCHEMICAL TRANSFORMATIONS OF THE LAKELAND LANDSCAPE

Peatlands modified hydrologically through channelling of the water streamflow from the catchment have become systems more closely linked with lake and river ecosystems of lower elevations. This gives the grounds to address a question about their role in supplying the waters with nutrients, which may contribute to better knowledge on linkage of the water bodies to the catchments (Likens 1984, Hillbricht-Ilkowska 1995).

The analysis performed in this work has revealed that phosphorus leaving the examined systems is derived from the peatlands themselves, as well as from their mineral bedrocks, this having been confirmed by significant correlations between the P loads with outflows of Fe and Ca. This corresponds well with a tendency for phosphate to be adsorbed on iron hydroxides (FeOOH) (Mortimer 1942) and to be bound with calcite ($CaCO_3$) to produce sparingly soluble apatite (Löfgren and Ryding 1985). As a consequence, pairs of components: P-Fe and P-Ca may be transported out of the catchment. A more detailed analysis has shown that outflow of phosphorus forms (PO_4-P and particulate P) from the modified peatlands with humic lakes and bogs is significantly related to iron ion efflux only. Relationship between phosphate and Fe and Ca occurs exclusively in outflow from the drained peatlands with meadows. This indicates that weathering of minerals (from apatite group) in the catchment influences effectively phosphorus transport through the drained peatlands. Strikingly, Ca load does not significantly influence outflow of particulate P from the examined meadow systems. This may possibly be an effect of a weaker affinity of phosphorus to Ca than Fe, in the flooded soils and sediments even fairly abundant in calcium carbonate (Golterman 1988).

Nevertheless, effluxes of essential elements from the peatlands depend on functioning of these ecosystems in seasonally changing hydrologic and biogeochemical conditions. The hydrochemical relationships described above and comprising P, Fe and Ca in outflowing waters represent only a part of the complex of watershed and atmospheric factors that affect loads of N and P in waters outflowing from the studied peatlands.

High concentrations of phosphate in streamflow from the catchment and disturbances in hydrology of the examined peatlands manifested by increased inflows, lowered water storage and high precipitation sums, are the most important factors increasing efflux of PO_4-P from the peatland watersheds, which may lead to eutrophication. It is noteworthy, that the highest rates of water flow and drops in water storage in the study region occur usually during spring (Stachurski and Zimka 1994, Kruk 1997b, c, d, e). In this way, the increased loads of PO_4-P from the mires to lake waters have the strongest eutrophying effect (Vollenveider 1976).

Increased water inflow from the catchment and lowered water storage also stimulate losses of other phosphorus forms: DOP and particulate P. This only relates to the modified peatlands with humic lakes and drained peatlands with meadows, where considerable losses of these forms were noted (Kruk 1997b, d, e). There is a lot of indications that draining of a natural peatland may increase by a few times the amount of phosphorus tied to organic suspended matter in outflowing waters (Sallantaus and Pätilä 1983), and further drain functioning does not change this effect. As a consequence, it is probable that hydrologic modifications of peatlands, drainage in particular, had carried and still carry a substantial load of particulate phosphorus into lakes. As a matter of fact, this phosphorus form does not result in direct eutrophication of a lake. However, in the course of time phosphates may be released in the anaerobic sediments and enter the cycle in a lake ecosystem (Harper 1992, Horne and Goldman 1994). It should be emphasised that yearly loads of particulate P discharged by the examined drained peatlands were twice as much as P-PO_4 loads (for instance, 0.08 kg PO_4-P *vs.* 0.16 kg of PP ha^{-1} yr^{-1}, calculated for area of the whole meadow-forest catchment). Considering widespread draining of peatlands in lakeland areas, this means that leaching of suspended particles containing phosphorus may be an important factor that enhances lake eutrophication.

Efflux of particulate phosphorus from the peatland with the eutrophied transitional bog is determined by other factors. The efflux is stimulated by increased concentrations of mineral nitrogen: ammonium in precipitation and nitrate in stream water from the catchment. Most likely, this is a response of the bog to eutrophication of the active peat layer, possibly an increase the detrital mass from more productive plant species (e.g. common reed) colonising in the peatland after the hydrologic modifications.

Outflow of another important component responsible for water eutrophication, namely nitrate, from the examined peatlands with humic lakes and bog is the larger, the higher is its concentration in the waters from catchment and the more rapid is the drop in water storage. Increased supply of NO_3-N from the land may result from various reasons, such as mineral fertilization, enhanced nitrification induced by e.g. forest tree harvesting (Bormann and Likens 1994), tree stand ageing (Reynolds and Edwards 1995) or draining of mires within a catchment (Kruk 1997a). There is very distinct relation between the increased nitrate transport and the peatland hydrology, i.e. lowering of water storage that broadens aerobic zone of the peatland, the phenomena favouring nitrification and losses of NO_3-N (Dowding 1981, Kirkham and Wilkins 1993). In general, efflux of this nitrogen form from a catchment is largely dependent on a complex of climatic and meteorologic factors (Mitchell et al. 1996). On the other hand, nitrate efflux from the examined drained peatlands with meadows depends strongly on one factor only, namely potassium content of the catchment waters. This relationship probably results from a common origin of both components, a part of which is being derived from mineral fertilizers, and additionally from considerable mobility of both ions in the saturated organic soils (Lityński and Jurkowska 1982).

Likewise, NH_4-N load in waters outflowing from the hydrologically modified peatlands increases as influenced by higher concentrations of this nitrogen form in the waters from catchment, as well as, by hydrologic factors. In addition, in the peatland with transitional bog, the NH_4-N load may be increased if precipitation carries larger quantities of magnesium and if the stream waters contain more potassium. This may suggest ionic exchange between these two metals and NH_4^+ within peat mosses (Bell 1959, Damman 1988). Then, increased effluxes of organic and particulate nitrogen may be attributed to processes of peat erosion by channell.

On a landscape scale, hydrologically modified peatlands may play various roles in water eutrophication. This applies especially to the group of peatlands that had been hydrologically modified by channelling and where mire habitat has been maintained, i.e. to the peatlands with humic lakes and bogs. Similarly to forest ecosystems (Zimka 1989), with an increase in nitrogen input, these peatlands exhibit a growing tendency to retain more amount of N. However, nitrogen retention in the peatlands is to some extent limited at higher N inputs, which may indicate exceedance of nitrogen retention capacity. In the case of the examined sites, it should be noted that quite high absolute values of N interception (about 200 kg $ha^{-1}yr^{-1}$) doesn't indicate any considerable N retention in relative values (Fig. 7, Table 4). Contrary, a higher phosphorus input is not accompanied by a proportional increase in its absolute retention. Phosphorus resources diminish at higher P supply. In this case, the difference between the peatlands and forest ecosystems is very clear: P retention in forests increases proportionally to P input (Zimka 1989). A characteristic feature of the considered peatlands seems to consist in proportional increase in absolute PO_4-P retention with increasing phosphorus input, whereas dissolved organic P balance becomes negative. Thus, under pressure of eutrophying factors from atmospheric and catchment sources, the peatlands incised with watercourses with humic lakes and bogs play a double role:

1. as ecotones that intercept more in absolute values nitrogen and phosphate phosphorus into the ecosystem cycling, which contributes to eutrophication of these systems,

2. as ecotones that convert phosphorus and lose it primarily in dissolved organic form at a rate proportional to P input, which contributes indirectly to eutrophication of aquatic ecosystems in lower elevations.

In the peatlands with still different hydrologic system, i.e. those effectively drained and used as meadows, the tendency to lose nutrient elements from the peatland resources is even more strongly marked than in the modified peatlands with humic lakes and bogs. It manifests in variable nitrogen retention along with increasing input of the element. Usually negative retention has been recorded here. It should be kept in mind that the systems are additionally supplied with nitrogen derived from fertilisers. The same tendency is also manifest in the case of phosphorus, the element being lost from the peatlands with increasing P load from the catchment and the atmosphere. In this case we can consider the drained peatlands with meadows as ecotones converting phosphorus, provided that the peatlands lose particulate forms of this element. It seems that these are losses of phosphorus carried by suspended particles in outflowing waters which determine specific role of meadow peatlands in eutrophication of lakes and rivers of lower elevations.

Is it, therefore, reasonable to consider the peatlands as ecotones decreasing loads of nutrient elements such as PO_4-P or NO_3-N, i.e.

those responsible for eutrophication? The retention effectiveness for the components in relation to their inputs (in %) suggests slight or at most inconsistent ability of the peatlands of retaining or converting these forms. Indeed, phosphate generally retains, but this is evident (more than 50%) at low supply only. Considerable and irregular variability in nitrate balances found for the examined peatland ecotones testifies that nitrate transport depends upon various local factors mentioned above. In comparison with a considerable decline in NO_3-N flow through undrained peatlands situated in depressions without runoff (Kruk 1990, 1997a), nitrogen cycling appears to be destabilised by the hydrologic modifications, particularly by "channelling" of the outflow and subsequent hydrologic "opening" of the peatlands.

It should be stressed, that peatland area in relation to other terrestrial ecosystems in the region of the Masurian Lakeland constitutes about 12.5%, which is typical proportion for other young postglacial terrains of Poland (Kondracki 1988) and Scandinavia, as well (Krug 1993). Despite such a small proportion, it should be realised that various peatlands of lower watershed parts are the pathway for large quantities of water flowing from morain uplands. Hence, the systems play a key role in matter transport through the landscape (Risser 1990).

To simplify, if no account is taken of urbanisation and industrialisation, it can be assumed that man activities that are of crucial importance for biogeochemical transformations of the present-day lakeland landscape comprise deforestation and changes in hydrologic conditions. The two latter activities determine the course of changes of the lakeland watersheds: from those forested with natural mires, through systems modified by e.g. forest drainage, meadow watersheds, to drainage systems of arable lands. It turns out that elemental transport in the outlined rank order of anthropogenic transformations in the watershed structure is also markedly altered (Figs 14–20). This biogeochemical transformation of the landscape is evident in the case of phosphorus and nitrogen retention dynamics. The decline in phosphorus retention capacity of forest ecosystems may be attributed to hydrologic manipulations in forest-peatland watersheds, whereas an analogous tendency for nitrogen is most likely connected with fertilisation and broadening acreage of arable fields in relation to meadows.

In the light of the above considerations, attention should be given to a recorded retention capacity of agricultural catchments in relation to phosphorus. Despite losses of particulate phosphorus from the drained peatlands with meadows found in this work, P transport through the whole watershed system is of limited importance. Although phosphorus is being discharged to outflowing waters, plant and soil accumulation of this element causes its retention to be clearly positive, and indices of P efflux from the agricultural watersheds do not differ significantly from those obtained for the forested catchments (Table 10). A comparison of the data indicates that the forested and agricultural watersheds both contribute to eutrophication of surface waters through supplying the waters with phosphorus. On the other hand, eutrophication due to nitrogen supply is enhanced by the latter watersheds, in particular.

Generally, deforestation, hydrologic modifications and reduction of meadow acreage have intensified matter transport from watersheds to aquatic ecosystems. Peatland ecotones situated between terrestrial and aquatic environments could possibly play the barrier role to a greater extent and neutralise at least partly the eutrophying effect of essential elements incoming from the managed watersheds. However, according to the results obtained in this work, hydrologic modifications, which disturb functioning of the ecotones, counteract the effect and presumably contribute to trophic degradation of numerous lakes. Thereby, a problem emerges of at least partial "renaturisation" or "reengineering" of the wetlands (Pfadenhauer and Kloetzli 1996, Middleton 1999).

However, optimisation of such activities in a broader natural system still needs comprehensive studying.

6. CONCLUSIONS

1. Hydrologically modified peatlands are systems, in which balanced transport of mineral components from the catchment and the atmosphere to aquatic ecosystems prevails. Tendencies to reduce throughflows of ammonium and phosphate ions are rather moderate, and those for trace metals (Zn, Cu, Pb and Cd) incoming mostly in precipitation are more evident. The barrier role of the examined peatlands is not marked, except for the trace metals mentioned.

2. The examined peatlands enrich the water runoff and consequently the entire hydrographic system with an extra load of minerals. This applies especially to dissolved organic phosphorus being removed from the modified peatlands with humic lakes, and particulate phosphorus, nitrate and such metals as Ca, Mg, Mn and Fe. being lost from the drained peatlands with meadows.

3. Eutrophication of the peatland with transitional bog incised with a water course results from higher inputs of mineral N and P forms from the catchment and the atmosphere, lower precipitation pH and higher SO_4-S content, as well as from raised water storage during winter and early spring. Influence of these factors explains changes in vegetation cover of the peatland from ombrophilous communities to more fertile ones.

4. Phosphorus efflux (PO_4-P and particulate P) from the examined peatlands is influenced by the internal biogeochemical system, this being indicated by its connection with efflux of Fe. An effect of geochemical processes occurring in mineral bedrock of the catchment, such as Ca leaching, is manifest in the drained peatlands with meadows.

5. Losses of the minerals from the examined peatlands may increase and enhance eutrophication of lakes and rivers of lower localities primarily due to catchment influence, that is, increased inflow of water containing mineral forms of N and P and also by lowering water storage in the peatlands. Losses of essential elements from the drained peatlands with meadows may be additionally increased by higher precipitation and a larger inflow of NH_4-N and K ions from the catchment.

6. On a landscape scale, the increased supply of N and P from the catchment and the atmosphere to the hydrologically modified peatlands with humic lakes and bogs causes the ecosystems to play double role: 1. as ecotones intercepting more and more amounts of nitrogen and phosphate phosphorus, which leads to eutrophication of their own habitats, and 2. as ecotones converting phosphorus and losing it primarily as dissolved organic forms, thus contributing indirectly to eutrophication of aquatic ecosystems of lower elevations.

7. In the spatial land – water systems, the drained peatlands with meadows receiving increasingly higher loads of N and P from the catchment and the atmosphere convert phosphorus and lose it in a particulate form and, because of additional losses of nitrogen, they may be considered as landscape components which pose increasing threat of eutrophication to lakes and rivers.

8. Outflows of all dissolved forms of nitrogen, sulphate, potassium, sodium, as well as manganese, zinc and copper are significantly higher from the agricultural catchments of various proportions of peatland area than from the forested watersheds with peatlands. No significant differences were found in the case of phosphorus effluxes.

9. The forested watersheds with peatlands exposed to increasingly intensive hydrologic modifications are characterised by a gradual reduction of phosphorus retention, which indicates possibility of water eutrophication due to hydrologic modifications in forest complexes.

10. A decrease in acreage of the peatlands managed as meadows in relation to arable field area is connected with almost proportional increase in losses of NO_3-N, SO_4-S, Ca, Mg, K, Na and Cu from the agricultural catchments, whereas losses of iron and manganese diminish.

11. Hydrologically modified peatlands constitute ecotones where man-induced long-term processes unfavourable for aquatic ecosystems overlap. Eutrophication of peatland habitats and eutrophying effect of the peatlands result from deforestation of the catchment as well as from hydrologic changes induced by drainage and regulation of hydrographic system. The present-day increase in pools of N and P compounds cycling within the environment, "disturbance" of climatic conditions, i.e. higher precipitation and rapid meteorologic events as well as "acid rains" will probably enhance eutrophication of peatland habitats and intensify the eutrophying effects of the peatlands ecotones on aquatic ecosystems of lakes and rivers.

ACKNOWLEDGEMENTS: This work comprised a wide variety of materials and thus its performance was possible through participation in several research programmes and thanks to kindness of many people. Its major part was financed by Scientific Research Committee (KBN) within the author's research project No 6PO5 071 06 performed in the years 1994 – 1997, although a considerable support was provided by a project 04.09 performed in Institute of Ecology of PASc in 1992 – 1994 and author's own project 05. 030.205 performed on Faculty of Waters and Inland Fishery of Academy of Agriculture and Technology (AR–T) in Olsztyn. I am deeply grateful to Professor Antoni Stachurski and Professor Jerzy Roman Zimka from Department of Plant Ecology of Institute of Ecology of PASc, as well as to Andrzej Tatur, DSc. from Department of Biogeochemistry of the same Institute for their help in metal analyses. Furthermore, I would like to thank very much to Leszek Kufel, DSc. from Hydrobiological Station of Institute of Ecology of PASc in Mikołajki and to Professor Mirosław Łuczyński from Department of Evolutionary Genetics in University of Warmia and Mazury in Olsztyn for their help and for being given the possibility to use laboratories. I am also grateful for helpful and inspiring remarks of reviewers, Professor Bogusław Zdanowski and Professor Michel McLaine (USA), as well as, for translation to Taida Tarabuła, DSc.

7. SUMMARY

This work aimed at assessing retention and losses of mineral components in/from hydrologically modified peatlands, at determining factors responsible for eutrophication of peatlands with bog and those affecting effluxes of essential elements (N and P) that favour eutrophication of water bodies, as well as at outlying tendencies to modify element cycling within lakeland watersheds due to changes in land use, deforestation and peatland drainage.

The studies were carried out at five peatland systems of the Masurian Lakeland: two peatlands with humic lakes and one peatland with transitional bog where hydrologic modification consisted in establishment of a channel and two drained peatlands managed as meadows – one of them was located in a forested area, and the other one was surrounded by arable fields. Additionally, numerous silvicultural and agricultural catchments with peatlands were included into the studies (Fig. 1). The examined mire systems had diverse vegetation cover characterised by visible transformations from ombrophilous bogs toward more fertile rushes and forest communities (Table 1).

The basic methodological approach was the balance: input from the atmosphere and the catchment – stream water runoff (Fig. 2). Many routine methods of hydrologic measurements, water sampling and analysing of mineral components were applied. In order to recognise factors affecting eutrophication processes, procedures of correlation, multiple regression and stepwise selection of statistically significant variables were used.

The investigated peatlands are supply by waters having a fairly variable chemical composition. The greatest hydrochemical differences occur between atmospheric precipitation and surface and subsurface waters. Higher concentrations of N, S, Ca and K were recorded in the agricultural than forested watersheds (Table 2 A, B). Hydrologic conditions of water flow through the hydrologically modified peatlands favour balanced transfer of minerals (Table 3).

In the modified peatlands with humic lakes and transitional bog, which are most open to water flow, transport of total nitrogen exhibits at most a slight tendency to be retained (Table 4). Among nitrogen forms, the mires retain consistently ammonium nitrogen only. There are no losses of nitrogen forms from the mires incised with watercourses. Nitrogen transport through the drained peatlands is similar, although the mid-forest peatland displays a more distinct tendency to loss nitrate nitrogen. The peatland in the agricultural landscape retains NH_4-N even in 70% of inflow (Table 4).

Both peatlands with humic lakes hardly retains phosphate phosphorus, whereas losses of organic phosphorus and, to a smaller extent, also particulate phosphorus are evident. As a consequence, retention of total phosphorus is negative (Table 4). The peatland

with transitional bog retains to a moderate extent all phosphorus forms, mostly PO4-P (Table 4). The drained peatlands are characterised by a more clear-cut retention of phosphate, more balanced transport of organic phosphorus and very clear losses of particulate phosphorus (Table 4). The modified peatlands retains at most very weakly SO4-S (Table 4).

In most peatlands investigated, flow of calcium, magnesium, potassium and sodium ions is balanced between the inflow from the catchment and outflow (Table 5). The only exception is the drained peatland with meadow in the agricultural landscape, where Ca and Mg are clearly removed (Table 5). In the case of Fe and Mn, losses of these elements predominate. Only the peatlands with humic lakes typically do not lose clearly any of the metals (Table 5). A characteristic feature of transport of dissolved forms of Zn, Cu, Pb and Cd is important contribution of atmospheric input. Moreover, these metals are strongly retained in the peatlands considered, especially in the drained peatlands with meadows (Table 5).

An analysis was performed in order to find hydrologic and biogeochemical factors responsible for retention of mineral components in the peatland with transitional bog during the growing and dormant seasons (Table 6). It appeared that eutrophication of the peatland through retention of mineral N and P forms during the growing season has been stimulated primarily by higher concentrations of these ions in waters inflowing from the catchment and the atmosphere and increased precipitation of lowered pH (Table 7). Then, retention of N and P forms in the boggy peatland during the dormant season depends mostly on N and P concentrations in the inflowing waters and rise of water storage (P retention), and additionally on SO4-S concentration in precipitation (N retention) (Table 7). Factors that determine retention of SO4-S and metals (Ca, Mg, K, Na and Mn) include most of all increases in water storage and sulphate concentration in the inflowing water (S retention), as well as modifying effects of nitrate ions (metal retention) (Table 7).

The examined peatlands are also a source of various essential elements that cause eutrophication of aquatic bodies of lower elevations. For this reason, hydrologic and biogeochemical factors responsible for losses of these elements from the peatlands were analysed. It has been found that monthly loads of PO4-P and particulate phosphorus are significantly correlated with loads of calcium and iron ions in runoff water (Figs 3–6). Efflux of these phosphorus forms is however determined by internal biogeochemical system of the peatlands, this having been confirmed by a relationship between the effluxes with Fe losses, whereas the influence of geochemical processes, such as Ca leaching from the mineral soils, plays increasingly important role in the peatlands covered by meadows with effectively drained watersheds (Table 8).

Taking into an account various hydrologic and hydrochemical factors it can be concluded that eutrophication of aquatic ecosystems receiving waters from the examined peatlands with humic lakes is associated with an increase in water inflow from the catchment and increased concentrations of mineral N and P forms in these waters (Table 9). In the case of peatlands with eutrophied bogs, leading factors responsible for higher losses of essential elements include increased concentrations of N and P in inflowing waters and a drop in water storage (Table 9). Increased effluxes of N and P from the drained peatlands with meadows are influenced by hydrologic factors such as higher water inflows from the catchment, higher precipitation, lowered water storage and higher concentrations of NH4-N and K in the waters inflowing from the catchment (Table 9).

Over-eutrophication of the peatlands modified by incision with a watercourse and with still existing mire habitat, and eutrophication of aquatic ecosystems by these peatlands may occur at the same time. The drained peatlands with meadows respond to increased loads of N and P differently. Along with an increase in yearly input of total nitrogen from the catchment and the atmosphere, the quantity of N retained in the modified peatlands with humic lakes and bogs increases (Fig. 7 A). No such a consistent increase in nitrogen retention with increasing input of the element could be noted in the drained peatlands (Fig. 7 B). Furthermore, a higher yearly load of phosphorus in waters supplying the peatlands has led even to losses of total P. The relationship is insignificant in the case of peatlands with humic lakes and bogs (Fig. 8 A), and significant for the drained peatlands with meadows (Fig. 8 B).

The next step was to analyse whether retention of particular P forms to the distinguished groups of the peatlands depends on the increased supply of total phosphorus. It appears that at higher loads of total P, phosphate is more tightly retained within the modified peatlands with existing mire habitats (Fig. 9 A). In the case of drained peatlands with meadows the response is different. Increased loads of total P result in fairly variable levels of phosphate retention (Fig. 9 B). Unlike phosphate, the increased loads of total P to the modified peatlands with humic lakes and bogs cause losses of dissolved organic phosphorus. This relationship is strongly correlated (Fig. 10 A). No such regularity is observed in the cultivated drained peatlands (Fig. 10 B). Balances of particulate phosphorus respond differently to P input. No significant relationship occurs between P input and retention or losses of particulate P from the modified peatlands with humic lakes and bogs (Fig. 11 A). In contrast, this P form is lost from the drained peatlands with meadows proportionally to P input (Fig. 11 B).

It appeared that nitrate may be retained or removed from the peatlands (Fig. 12 A and B) but phosphate phosphorus is generally retained in both peatland groups, regardless of PO4-P input (Fig. 13 A and B). However, the modified peatlands with remained mire habitat exhibited clear regularity, according to which the PO_4-P retention represents the smaller percentage of the input, the larger is PO_4-P input from the catchment and the atmosphere.

In the general pattern of anthropogenic pressure, a stage may be distinguished of hydrologic transformations of forested watersheds consisting in increasing proportion of drained peatlands and a stage of intensive agriculture represented by increased proportion of arable fields at the expense of peaty meadows in the catchment. A comparison of effluxes of mineral components from a few watersheds in the silvicultural and agricultural landscapes already points out significant differences in transport of elements. The effluxes of majority analysed components are significantly higher in the case of agricultural than silvicultural catchments. This applies to all dissolved nitrogen forms, sulphate, potassium, sodium and microelements: manganese, zinc and copper. The differences are insignificant in the case of phosphorus forms (Table 10).

Both watershed types, silvicultural and agricultural ones display a tendency to retain most nitrogen forms, and hydrologic modifications do not diversify it (Fig. 14). The only exception is nitrate nitrogen, retention of which is being diversified. The lower proportion of meadows in the agricultural catchment, the more negative NO_3-N retention, which means the greater NO_3-N and hence total nitrogen export to aquatic ecosystems (Fig. 14). Increasing degree of hydrologic modifications of peatland forest watersheds is connected with a gradual decrease in phosphorus retention, which indicates possibility of water eutrophication through drainage of forested areas. On the other hand, agricultural catchments consistently retain the element (Fig. 15). As an area of the peatlands managed as meadows in relation to the area of arable fields decreases, SO_4-S (Fig. 16), Ca, Mg (Fig. 17) and K and Na (Fig. 18) losses from the agricultural watersheds increase in a more or less proportional way, whereas losses of iron and manganese become reduced (Fig. 19). Level of zinc accumulation is stable in catchment of both types, but slightly higher in the forested watersheds (Fig. 19). In the watersheds of the latter type, Cu is intensively accumulated, whereas in the agricultural ones, a gradual decrease in retention of the element occurs with disappearance of meadows (Fig. 20). Lead and cadmium accumulate in all the catchments at similar levels (Fig. 20).

In discussion, an influence of the hydrologic modifications on element transport through the peatlands was considered. Furthermore, on the basis of the literature data, retention of elements was compared among bogs having unchanged and modified hydrologic systems (Table 11) and for peatlands in agricultural areas (Table 12). Peatland role in water eutrophication and biogeochemical transformations of the lakeland landscape was discussed.

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(*Received after revising December1999*)