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EFFECT OF DRAINING ON NITROGEN FLOW THROUGH MIRES IN AGRICULTURAL LANDSCAPE

ABSTRACT: The objective of this work was to present seasonal dynamics of flow of nitrogen forms through fens prior to and just after their drainage, as well as to demonstrate relationships between parameters of the flow. Inflow of inorganic nitrogen forms to undrained mires clearly predominates outflow, whereas remarkable losses of N–NO$_3$ occur after mire drainage. An influence of hydrochemical parameters – N-NH$_4$, N–NO$_3$ and DON concentrations in subsurface water inflowing to two undrained mires and volume of water inflow on budgets (inflow - outflow) of nitrogen forms was examined. The analysis was performed for months when the mires were flooded and for the dry period, separately. Budgets of inorganic nitrogen forms are clearly affected by their concentrations in inflow water. During the wet period, hydrological factor plays also certain role. Inflow of N–NO$_3$ and N-NH$_4$ significantly influenced DON budget. Moreover, some interactions between DON and N-NH$_4$ was found.

KEY WORDS: nitrogen, mires, drainage, inflow, outflow, budget

1. INTRODUCTION

Nitrogen cycling in mire ecosystems is essential for trophic status of these environments and transformations of mire vegetation. It is also important as mires are linked with terrestrial as well as water ecosystems in a landscape scale. Cycling of main dissolved forms of nitrogen becomes crucial in landscape influenced by agriculture supported by fertilization. This is because ions, nitrate in particular, which have not been taken up by crop plants nor adsorbed by the soil, are leached from fields to ground water (being the source of water for mires situated downwards) (Lityński and Jurkowska 1982). Even under such circumstances, undrained mire ecosystems exhibit an apparent tendency to reduce nitrogen outflow, with denitrification being the main mechanism removing excess of nitrogen (Barlett et al. 1979, Brinson et al. 1984, Gilliam et al. 1988). Among other processes which continuously or periodically remove nitrogen ions from wetlands, a special attention should be paid to ammonia diffusion (Gambrell and Patrick 1978), NH_4^+ immobilization in peat (Ulehova 1971, Brinson et al. 1984) and N retention in biomass, especially that of perennial plants (Wilpiszewska 1990). Mire drainage – rapid water run-off followed by drain functioning – destroys soil mechanisms conducive to reduction of nitrogen flow (Ponnamperuma 1972).

In this work, nitrogen flow through a mire system is understood as transfer of dissolved forms of nitrogen from the zone of water inflow from the catchment to the zone of outflow from the mire, as is schematically shown in Fig. 1. The studies were carried out at fens located in hollows with no surface run-off characteristic of lakeland, where typically, both inflow and outflow are subsurface waters. Nitrogen input from the atmosphere was neglected due to its little contribution to nitrogen budget in the examined systems (Kruk 1990).

A general objective of this work is to present nitrogen flow through mire systems and interrelationships between main inorganic forms of nitrogen: nitrate ($N-NO_3$), ammonium ($N-NH_4$) and dissolved organic nitrogen (DON). The analysis concerns three different hydrological situations:

1. when the mires are flooded (winter-spring),
2. when for some natural reasons (summer increase in evapotranspiration), water level does not reach the mire surface (summer – autumn) (Fig. 1) and,
3. when hydrological conditions are artificially altered by drainage.

Parameters characterizing the processes of nitrogen transport through mires included ground water inflow and outflow of nitrogen (loads), and mainly the values of nitrogen budget (inflow – outflow). Moreover, concentrations in inflow and surface waters were also taken into account.

An important supplement to the study on the dynamics of nitrogen flow through mire systems is to present a pattern of interrelations between the parameters examined. When expressed in a form of budgets (inflow – outflow), the relationships enable to identify factors affecting nitrogen flow through wetlands. In some studies multiple regression has been applied which allows to get an insight into mechanisms controlling element flux through such complicated natural systems like tree canopies (Stachurski 1987) or a forested catchment (Zimka 1989).

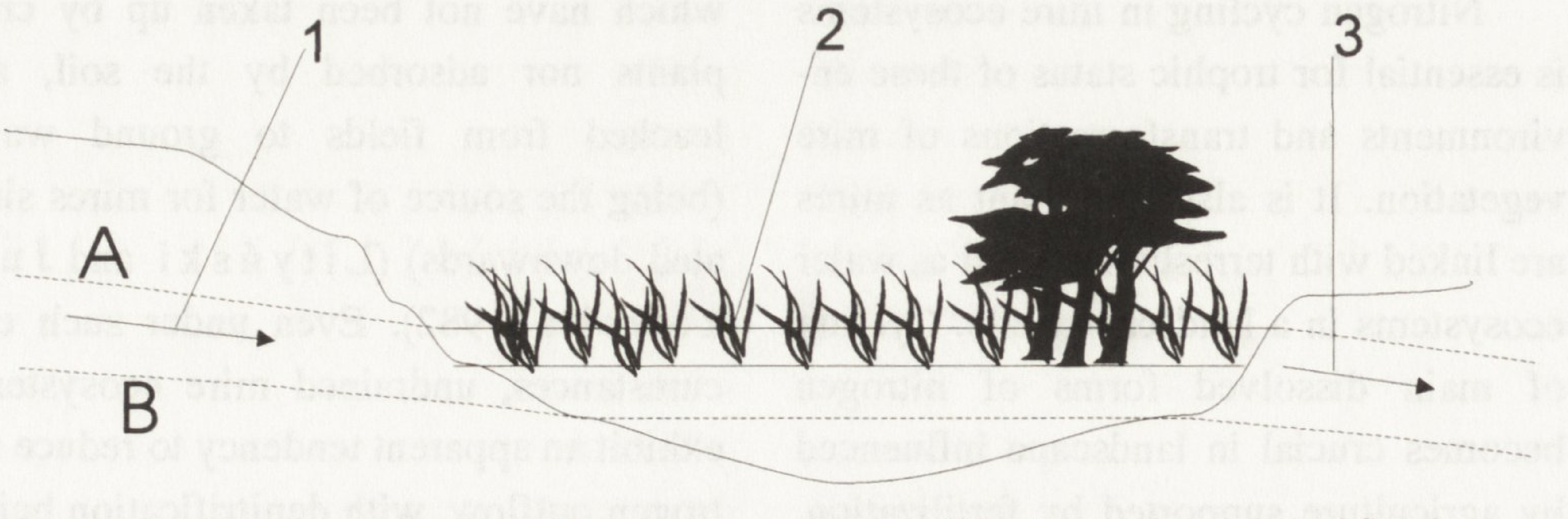

Fig. 1. A pattern of water flow through the ecosystem of fen type in the period of flood – winter-spring (A) and without the flood – summer-autumn (B)
1 – subsurface water inflow, 2 – surface water, 3 – subsurface water outflow

It may be expected that such a statistical approach would lead to a better understanding of interrelationships between the examined factors. It would also make it possible to explain some phenomena observed in studies on biogeochemical budgets in mire systems, especially different economy of inorganic against organic nitrogen by a mire (Kruk 1990). Furthermore, a thorough analysis was necessary to reveal the importance of an astatical mire basin in altering total nitrogen concentration during the process of its flow through the mire (Kruk 1996). Finally, there is interesting to analyse the role of hydrological factor in the context of reduced stability of water cycle in agricultural landscape and frequent man's interference (melioration).

A practical aspect of the studies should also be mentioned. A reaction of nitrogen flow on drainage may be useful for evaluation of the consequences on lakes of lower localities, for instance. Moreover, the interrelationships between parameters involved in the process of nitrogen flow through fens (with *Typha latifolia* as one of the main components) may be used to predict a system response to controlled nitrogen loads derived from secondary sewage plants and delivered to the communities of macrophytes (Tilton and Kadlec 1979, Nichols 1983).

2. STUDY AREA

Two mire systems of fen type located in hollows with no surface run-off in Masurian Lakeland within Jorka river watershed near Jorzec and Inulec lakes west of Mikołajki were chosen to the studies (Fig. 2). The mires represent ecosystems occurring commonly not only in Masurian Lakeland but throughout the young

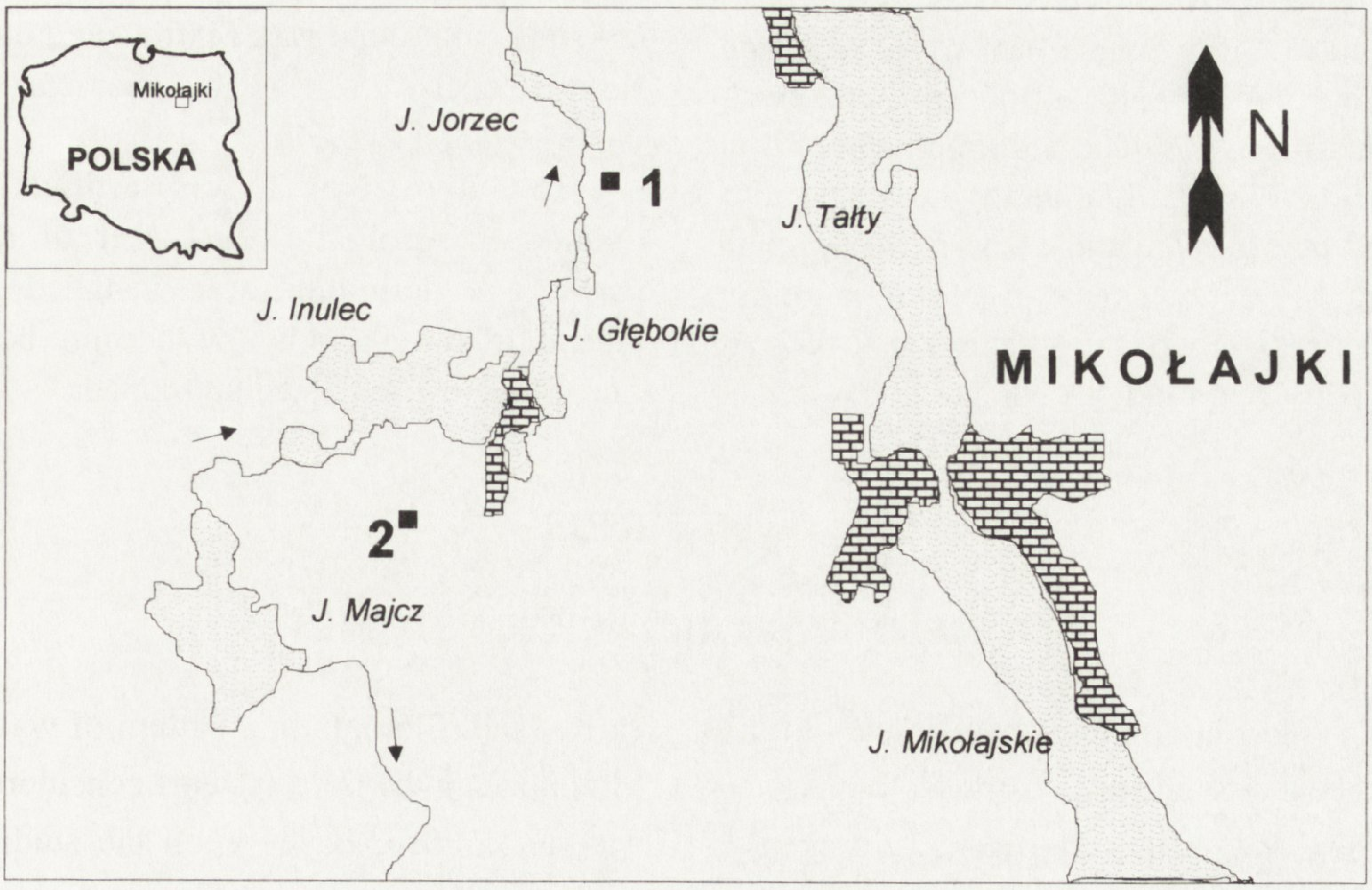

Fig. 2. Location of the examined mires (1, 2) near Mikołajki (Masurian Lakeland, NE Poland)

glacial lakeland zone. They are located in hollows of melt-out origin, without surface run-off, and overgrown with fen vegetation. Agricultural environs of the mires results in such anthropogenic processes as accumulation of slope material, disturbances in natural succession of plants, or receiving inorganic elements leached from fertilized fields (Kloss et al. 1987). The level of nitrogen fertilization in the study period ranged from 50 to 100 kg ha^{-1}.

The mire located in vicinity to the Jorzec lake (No 1 in Fig. 2) is small and has an area of 510 m^2. It is covered by association of cattail (*Typhetum latifoliae* Soo 1927). The basement soil comprised clayey-silty warp, and underneath, there was a layer of well-decomposed lowmoor peat (alder peat) underbedded directly by boulder clay. During the study period, from November till June, the mire was flooded, with water level being subject to fairly considerable fluctuations (approx. 60 cm). Thickness of peat and warp layers along which water flowed amounted to 50 cm at low water level, and to 140 when surface water appeared. The zone of water inflow from the catchment area included a through slope of up to 0.25 inclination being under agricultural use (ploughland). The soil was made up of loamy sands of morainic origin. Permeability of the soil and occurrence of hydrologic gradients of ground water tables determine flowable nature of the mire hydrological system (Kruk 1990).

The second selected mire is situated south of the Inulec lake (No 2 in Fig. 2). It is characterized by larger area (1830 m^2) and occurrence of two dominant associations of marshy vegetation: willow shrubberies (*Salicetum pentandro-cinereae* Almq. 1929 (Pass. 1961) and cattail rushes *Typhetum latifoliae* – Soo 1927. Soil basement consists of lowmoor peat, mainly strongly or moderately decomposed tall-sedge peat underlying a clayey-silty warp of variable thickness. Underneath the peat layer, detritus gyttja and clay layers occur. The layer, along which horizontal movement of water took place was peat of a thickness of 380 cm, though at low water levels it was reduced to 80 cm. The depth of surface water body reached 80 cm. The catchment area was made up of loam and loamy sand. During the study period the area was under agricultural use (cultivated field and a green crop). Occurrence of impermeable layers in the mire floor and clear-cut zones of ground water inflow and outflow are decisive of flowable character of the mire (Kruk 1990).

The mire No 2 was artificially drained in April after first year of the studies. A drain-pipe was installed at a depth of ca. 70 cm below the mire bed. The mire No 1 remained undrained.

3. METHODS

3.1. FIELD AND LABORATORY STUDIES

In order to assess inflow and outflow of selected nitrogen forms ($N–NH_4$, $N–NO_3$ and dissolved organic nitrogen) a wide range of hydrological, hydrogeological and hydrochemical analyses were carried out. First of all, a pattern of water flow through the mire systems considered was determined. Based upon the studies on hydraulic gradients of ground water table (with use of piezometer system and measurements performed with geodetic theodolite) and ground permeability (measurement rate of raise of artificially lowered water table according to Pisarkov (Wieczysty 1982)) the zones of water inflow and outflow from the wetlands were determined, and then throughflow values were calculated on the basis of Darcy's law (Pazdro 1983). In this purpose, a system of piezometers was installed (5 around the smaller mire No 1, and 6 – around the larger mire No 2) to measure levels and gradients of inflow and outflow water tables (Kruk 1990). Drainage outflow was calculated after Kostjakov method (Wieczysty 1982). The pattern of flow determined thereby, and presented in a form of ideogram in Fig. 1, was a basis for calculating values of hydrological inflows and loads of nitrogen forms flowing in and out of the mires, that yielded budget values (inflow – outflow). The loads of particular compounds were figured out from the following formula:

$$L = \frac{Q \cdot S}{t}$$

where: L – load of a compound, Q – water discharge, S – concentration of a compound, t – time. The loads of the examined nitrogen forms were expressed in $g\ m^{-2}\ month^{-1}$.

Water samples for nitrogen determination were taken once a month during the period of two years (May 1982 – May 1984). Water was collected from fixed inflow and outflow zones and from the central part of the surface water body. Ground water samples were taken from piezometers (made of PVC) of a diameter of 17 cm and a length comprising 80-100% of water throughflow section. Prior to sampling, piezometers were emptied of water they contained, and water refilling piezometers was taken up for analysis. After artificial drainage of the mire No 2, outflowing water was sampled from the drain-pipe or, when water level did not reach the drain – from the layer underneath – from piezometer (Kruk 1990). Water samples of a volume of 3–5 l was then filtered through GF/F Whatman glass filters and vaporized at 60° C after the samples had been divided between two evaporating dishes (0.5 l). One dish was supplied with 1–2 mg of salicylic acid to reduce sample pH to below 3. This prevented ammonia release during vaporisation. Similar amount of NaOH was added to the second dish in order to increase pH to over 11 (Stachurski and Zimka 1984).

Concentrations of ammonium ion and dissolved organic nitrogen were assessed by using a method for total nitrogen determination with gaseous chromatograph (CHN). Total nitrogen was determined in precipitate after vaporisation of water sample with salicylic acid addition. Total nitrogen was acquired by multiplying precipitate content in 1 l by nitrogen concentration in the precipitate. Ammonium contents in water samples were calculated as a difference between total nitrogen and nitrogen content found in the sample with addition of NaOH assessed by the same method (it was assumed that entire ammonia nitrogen would pass into gaseous phase at water pH equal to ca. 11) (Stachurski 1987). Nitrate nitrogen concentration was measured potentiometrically, and content of dissolved organic nitrogen (DON) was calculated indirectly as a difference between total nitrogen and the sum of ammonium and nitrate contents.

3.2. STATISTICAL ANALYSIS

Statistical analysis of the data collected included t-test of equality of two means from independent populations and multiple regression analysis with stepwise variable selection. Data processing was based upon an assumption that during the period of functioning, both mires (undisturbed by artificial drainage) were sufficiently similar to merge the hydrochemical and hydrological measurements into one data series for statistical analysis. Both sites, No 1 and 2, were overgrown with rush vegetation dominated by *Typhetum latifoliae* community in 100 and 70%, respectively. In the soils of both sites lowmoor peat occur covered by a layer of mineral warp of slope origin. Water moves through the examined mires from the inflow zones at slope bases through the layers of deposits of similar thickness to the zones of ground water run-off. Water level oscillations and variations in water retention over a year period are similar at both sites (Kruk 1990). Some differences between the sites occur in loads of nitrogen entering the mires. The differences result from limited fertilization of the catchment area of the mire No 2. The data series were analysed for both mires together for the periods when a surface water body was present or absent simultaneously at both sites. During the first year of the studies, the wet period (with the presence of water body) occurred in June and from November till June (9 months) in case of the mire No 1, and in May, June and from January till April (6 months) in case of the mire No 2. In the second year of the studies, it was only the mire No 1 that was flooded during the period January – May (5 months). Thereby 20 sets of samples were taken up representing the wet period. The mire No 1 was not flooded during the periods July – October (in the first year) and July – December (in the second year) (10 months). Likewise, surface water was absent at the mire No 2 between July and December (6 months) in the first year. Therefore, in total 16 sets of samples representing the dry period (with no surface water) were taken. Twelve sets of samples were, in turn, characteristic of the period following drainage of the mire No 2. These data were not included in statistical analysis with regression method due to insufficient number of the samples.

With a view to demonstrate interrelationships between parameters controlling the process of nitrogen flow through the mire ecosystems, regression analysis with stepwise variable selection model was employed (Guilford 1960). Calculations of coefficients of multiple regression, coefficients of determination, as well as Student t-test analysis determining significance level of the examined independent variables (biogeochemical and hydrological parameters), and then variable selection were performed by using computer software Statgraphics (Dąbkowski 1992).

Selection of independent variables to determine how they influence particular parameters (those characterizing nitrogen flow through the mires) was conducted in accordance with subsequent stages of water movement through the examined mires (Fig. 1). Thus, nitrogen budgets (in g m^{-2}) were investigated for being influenced by contents of nitrogen forms (in mg l^{-1}) in water inflowing to a mire, as well as concentration of these forms in surface water, while the latter parameter was examined for being affected by concentrations in inflow water only. Furthermore, an influence of ground water inflow (in mm) on hydrochemical parameters was examined. Based upon the method outlined above, a series of regression equations was obtained. After exclusion of statistically insignificant variables (significance levels of regression coefficients > 0.05), it became a basis for constructing a pattern of interaction power between factors affecting nitrogen flow through the mire systems. In order to assess how independent variables contributed to the prediction of the dependent variable, partial correlation was applied (Guilford 1960).

4. RESULTS

4.1. FLOW OF NITROGEN FORMS THROUGH THE MIRES DURING A YEAR

A phenomenon typical for the examined mire ecosystems is periodical occurrence of surface waters. In case of the examined mires, rapid fluctuations of inputs of all nitrogen forms were characteristic of water-abundant periods (November or January – June) (Figs 3 and 4). At that time, especially in early-spring months (March – April), nitrogen inflows reached their maximal values. Nevertheless, magnitude and ranges of nitrogen inflows differed between two years of the studies. It is clearly visible in case of the mire No 1, and the reasons of this should be suspected in smaller precipitation amount and milder season of snow-melt (Fig. 3). Nitrogen outflow during the wet period is not as rapid as nitrogen inflow and, as a rule, reaches lower values (except for DON outflow). Differences between inflow and outflow of $N–NO_3$, and $N–NH_4$ for majority of months, are then remarkable (Figs 3 and 4).

During the periods when surface water was lacking, i.e. from July till October or December, fluctuations in inflow and outflow of the components examined were distinctly less dynamic, and their values tended toward stabilizing at similar levels. Nevertheless, DON flow varied reaching considerable values (Figs 3 and 4).

Nitrogen flow through a mire system (mire No 2) completely changed after the mire drainage. Drain functioning can be divided into two periods. First period was associated with intensive outflow of water from the mire basin (April) and lasted ca. 10 days. During the second period, the drain prevented water retention in the mire and water appearing at the mire surface (Fig. 4). During the first period (of water run-off), outflow values of all nitrogen forms sharply increased. However, directly after water level had stabilized, a tendency to balance inflow against outflow became apparent. This continued approximately till November. Thereafter, certain, and in case of $N–NO_3$ – considerable differentiation of the examined parameters took place, with predominance of outflow over inflow (Fig. 4). This coincides with the period when the flood occurred at the undrained mire No 1 in that year.

With the aim of attaining some general information on differences in the flow of nitrogen forms through the examined mire systems among three hydrological situations (undrained covered with water, undrained with no surface water and drained), the data from the two similar mires was assigned to the situations mentioned (Chapter 3.2), and then com-

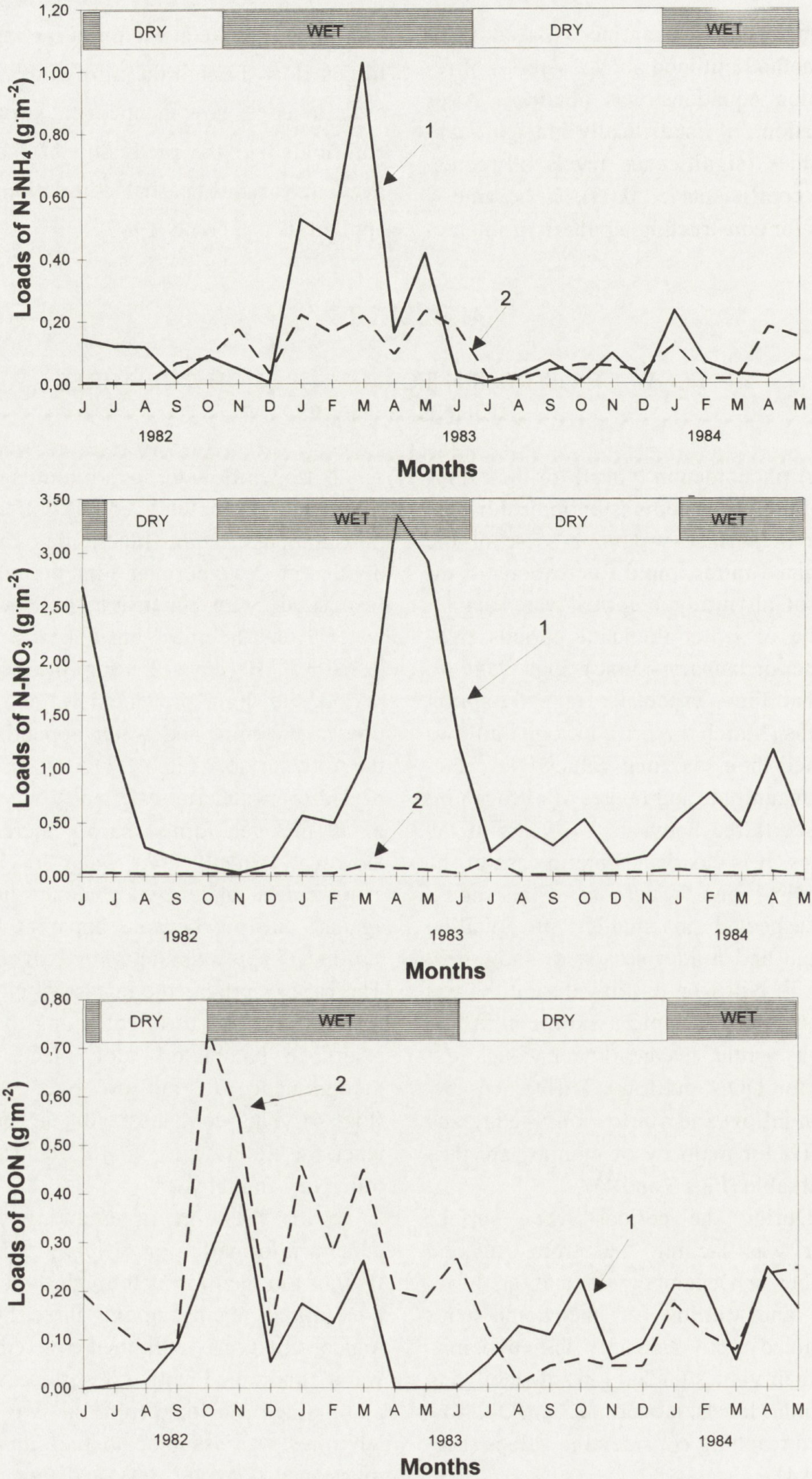

Fig. 3. Seasonal dynamics of inflow and outflow of N–NH$_4$, N–NO$_3$ and DON (g m^{-2} month^{-1}) in the undrained mire No 1
1 – inflow, 2 – outflow

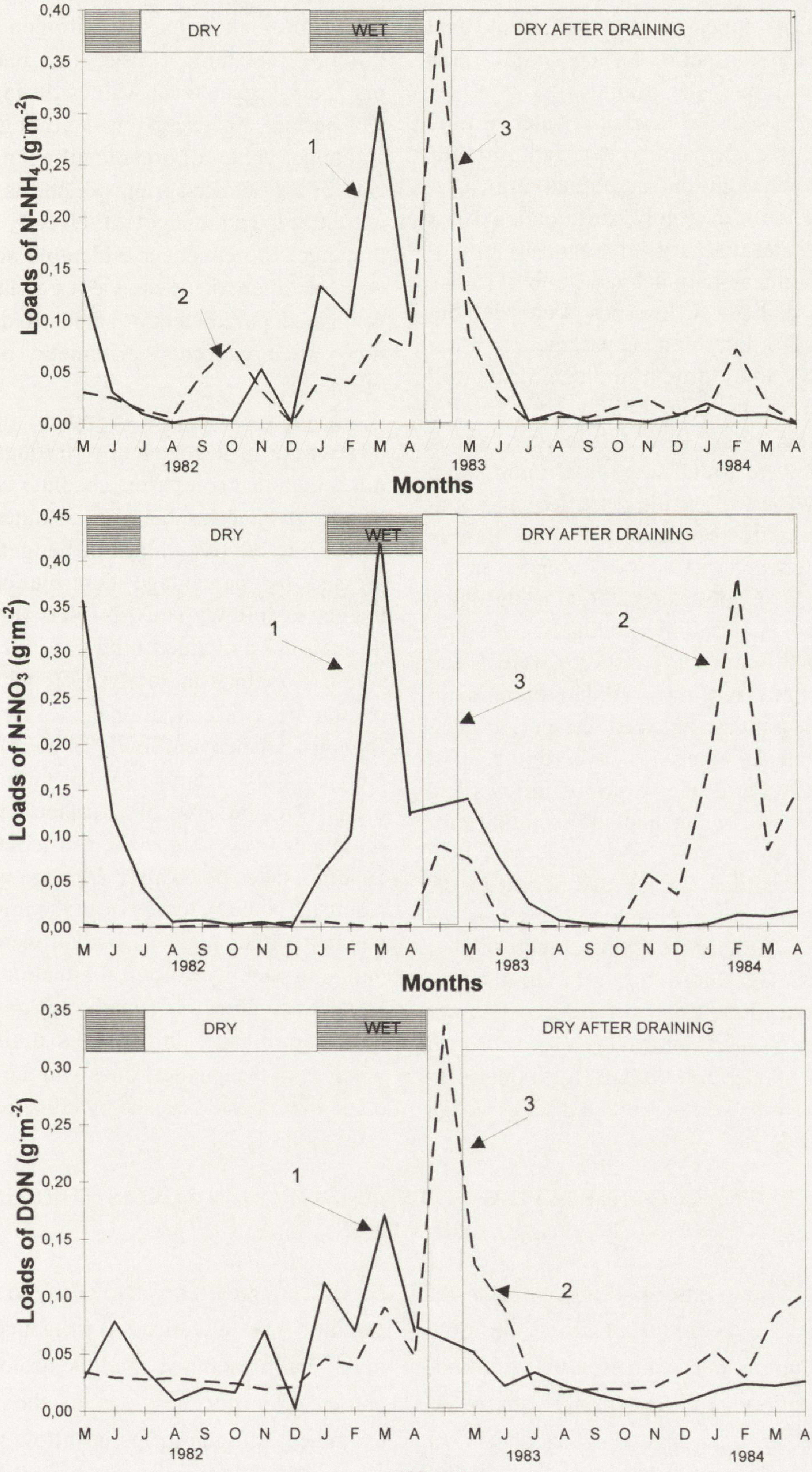

Fig. 4. Seasonal dynamics of inflow and outflow of N–NH$_4$, N–NO$_3$ and DON (g m^{-2} month^{-1}) in the mire No 2 prior to and after its drainage
1 – inflow, 2 – outflow, 3 – drainage application, time of rapid water run-off from the mire basin (ca. 10 days)

pared. It appeared that during the wet winter-spring period (when the mire was flooded) and the summer–autumn dry period (with no surface water in the mire), the flow of water and nitrogen forms through the undrained mire systems were markedly differentiated for both water discharge and majority of biogeochemical parameters (Table 1). The most distinct differences were demonstrated for hydrological parameters: water inflow and outflow from the mire, as well as for ammonium outflow ($p < 0.001$). Statistically significant differences at $p < 0.005$ were found in case of ammonium inflow, as well as nitrate inflow and budget. Significance level $p < 0.05$ was, in turn, characteristic of differences in inflows and outflows of organic nitrogen, as well as ammonium budgets. No significant differences ($p > 0.05$) were found for nitrate outflows, neither organic nitrogen budgets between the periods distinguished (Table 1). After drainage of the mire No 2, the values of inflows and outflows of water and the examined nitrogen forms were, as a rule, lower than those recorded for the dry period in the undrained mires. Nitrate outflow was the only parameter reaching much higher values than those observed in the undrained mires. Clear differences also occurred in case of budgets of nitrogen forms – negative values for both inorganic forms were recorded after drainage (Table 1).

Almost all values of nitrogen flow through the mire ecosystems reached markedly higher mean values during the wet period. An exception were negative and lower values of organic nitrogen budgets in the winter-spring period, as well as outflow and budget of $N–NO_3$ after drainage. Moreover, considerable scatter was characteristic of the values of the investigated parameters – standard deviations often exceeded arithmetic means (Table 1).

Even more clear-cut picture of the differences in nitrogen flow through the mires than that comparing absolute values of the parameters can be obtained by comparing relative values of budgets expressed by percentage contribution of budget to inflow. Thus, $N–NH_4$ flowing through the undrained mire covered with water is retained in nearly 50%, whereas natural or artificial drainage causes inflow to balance outflow (Table 1). $N–NO_3$ is tightly retained by the undrained mires (regardless of surface water presence) – even in 90%, but a reverse situation takes place after drainage which results in $N–NO_3$ losses from the mire. In contrast values of DON budget were negative in each hydrological situation, and DON was subject to (relatively) greatest losses from the mire after its drainage, whereas to the smallest ones – in the period of water deficit caused by climatic factors (Table 1).

4.2. FACTORS CONTROLLING FLOW OF NITROGEN FORMS THROUGH THE MIRES

The amounts of nitrogen forms retained, and/or removed from the flow each month, and expressed by their budgets (inflow – outflow) result from the interaction of a range of biogeochemical factors. The objective of the analysis presented thereafter was to verify to what extent, if any, the process is influenced by main hydrochemical and hydrological parameters: concentrations of the three examined nitrogen forms in inflow water (in mg l^{-1}) and amount of water inflowing

Table 1. A comparison of hydrological parameters and components of monthly flows of nitrogen forms through two undrained mires in the wet period – with a surface water (January – June) and dry period – without a surface water (July – December) over 2-year period, and after drainage over one year
t-test was applied to verify a hypothesis of equality of two means from independent populations

Hydrological conditions of mires	Hydrology		N inflow to mires			N outflow from mires			N budget Inflow – Outflow (in % of inflow)			N concentration in surface water		
	Inflow	Outflow	N–NH$_4$	N–NO$_3$	DON	N–NH$_4$	N–NO$_3$	DON	N–NH$_4$	N–NO$_3$	DON	N–NH$_4$	N–NO$_3$	DON
	(mm month^{-1})		(g m^{-2} month^{-1})									(mg l^{-1})		
Undrained with the surface water (wet period) (n = 20)	152.8 ± 74.6	126.9 ± 79.6	0.21 ± 0.25	0.86 ± 0.99	0.12 ± 0.11	0.11 ± 0.08	0.03 ± 0.03	0.19 ± 0.15	0.10 ± 0.21 *(48)*	0.83 ± 0.97 *(97)*	0.07 ± 0.12 *(–58)*	0.90 ± 0.72	0.36 ± 0.89	1.83 ± 1.63
Undrained without a surface water (dry period) (n = 16)	72.5 ± 47.8	52.9 ± 19.6	0.039 ± 0.05	0.23 ± 0.32	0.07 ± 0.08	0.034 ± 0.03	0.025 ± 0.04	0.09 ± 0.18	0.005 ± 0.06 *(13)*	0.20 ± 0.31 *(87)*	–0.019 ± 0.14 *(–26)*	–	–	–
p	<0.001	<0.001	<0.005	<0.005	<0.05	<0.001	>0.05	<0.05	<0.05	<0.005	>0.05	–	–	–
Drained (n = 12)	37.7 ± 20.6	41.2 ± 26.5	0.021 ± 0.04	0.024 ± 0.04	0.021 ± 0.01	0.024 ± 0.03	0.08 ± 0.11	0.05 ± 0.04	0.002 ± 0.03 *(–11)*	0.056 ± 0.12 *(–233)*	–0.030 ± 0.03 *(–143)*	–	–	–

to the mires (in mm). Additionally, concentrations of nitrogen forms in surface water (in mg l^{-1}) were included into the set of factors for the period when the mires were flooded. Within the flow pattern, an attempt was made to determine how inflow of subsurface water and concentrations of nitrogen forms in water inflowing from the catchment influence N–NH_4, N–NO_3 and DON concentrations in surface water, as well as how the concentrations in surface water are interrelated. To evaluate the strength of the interrelations between the factors constituting the flow pattern, partial correlations were computed (see: Methods). Thereby, contributions of each independent variable to the prediction of the dependent variable from the multiple regression equations contained in Tables 2–4 were determined.

In the period when mire surfaces were flooded (winter – spring), differences between factors controlling flow of inorganic nitrogen forms from one hand, and organic nitrogen – from the other hand, became apparent. A decline in outflows of ammonium and nitrate ions expressed in a form of budgets clearly depends upon inflow of these components with water derived from the drainage basin, with a stronger effect of their concentrations than water inflow alone. In case of N–NH_4 budget, concentration in inflow water accounts for 50% of its variability, whereas hydrological parameter – for 36%. Ammonium flow is additionally affected to a slight degree by concentrations of that ion in surface water (3% of the variability). Even more pronounced difference between hydrochemical and hydrological factor occurred in case of their effect on N–NO_3 budget – 82% and 12%, respectively (Fig. 5). Together, the factors discussed determine to a high degree the budgets of inorganic nitrogen forms, N-NH_4 in 89%, and N–NO_3 – in 94% (R^2 in Table 2). In contrast to the inorganic nitrogen flow, a negative value of DON budget in the water-abundant period (Table 1) depends mainly on N-NO_3 concentration in water derived from the catchment. This parameter is responsible for 26% of the variability of the budget considered. Additionally, organic nitrogen flow is influenced by ammonium concentration in inflow water (14% of its variability), as well as in surface water (15% of its variability) (Fig. 5). All of the three parameters determine DON budget in 56% (R^2 in Table 2).

Table 2. Monthly budgets (inflows – outflows) of nitrogen forms flowing through undrained mire systems in the wet period (with the surface water) in g m^{-2} $month^{-1}$ (dependent variables) as functions of subsurface water inflow to the mires in mm $month^{-1}$, concentrations of nitrogen forms in inflow and surface waters - both in mg l^{-1} (independent variables)
Independent variables included after stepwise selection: Inh – N–NH_4 concentrations in inflow water (mg l^{-1}), IH – subsurface water inflow (mm $month^{-1}$), Rnh – N–NH_4 concentrations in surface water (mg l^{-1}), Ino – N–NO_3 concentrations in inflow water (mg l^{-1}) (n = 20)

Budgets (inflow – outflow)	Independent variables and regression coefficients $a \pm b_1 \pm ... \pm b_n$ significance level of b coefficient,	Coefficient of determination (R^2 in %)	Significance level of R (p)
N–NH_4	–0.189 + 0.154 (Inh)+ 0.0012 (IH) – 0.061 (Rnh) p = 0.0005 p = 0.0062 p = 0.0298	89	$p < 0.01$
N–NO_3	–0.599 + 0.178 (Ino) + 0.0034 (IH) p = 0.0000 p = 0.0007	94	$p < 0.01$
DON	0.126 – 0.014 (Ino) – 0.069 (Rnh) – 0.056 (Inh) p = 0.0048 p = 0.0287 p = 0.0423	56	$p < 0.01$

Table 3. Concentrations of nitrogen forms in water of the mire basins in mg l^{-1} (dependent variables) as functions of concentrations of nitrogen forms in subsurface water inflowing to the mires in mg l^{-1} and concentrations of accompanying nitrogen forms in surface water in mg l^{-1} (independent variables) Independent variables included after stepwise selection: Rdo – DON concentration in surface water (mg l^{-1}), Ido – DON concentration in inflowing water (mg l^{-1}), Rnh – N–NH_4 concentration in surface water (mg l^{-1}) (n = 20)

Concentrations in water of mire basins	Independent variables and regression coefficients $a \pm b_1 \pm \dots \pm b_n$, Significance level of b coefficient	Coefficient of determination (R^2 in %)	Significance level of R (p)
N–NH_4	0.317 + 0.32 (Rdo) p = 0.0003	52	$p < 0.05$
N–NO_3	–	0	–
DON	0.275 + 0.863 (Ido) + 0.765 (Rnh) p = 0.0001 p = 0.0192	81	$p < 0.01$

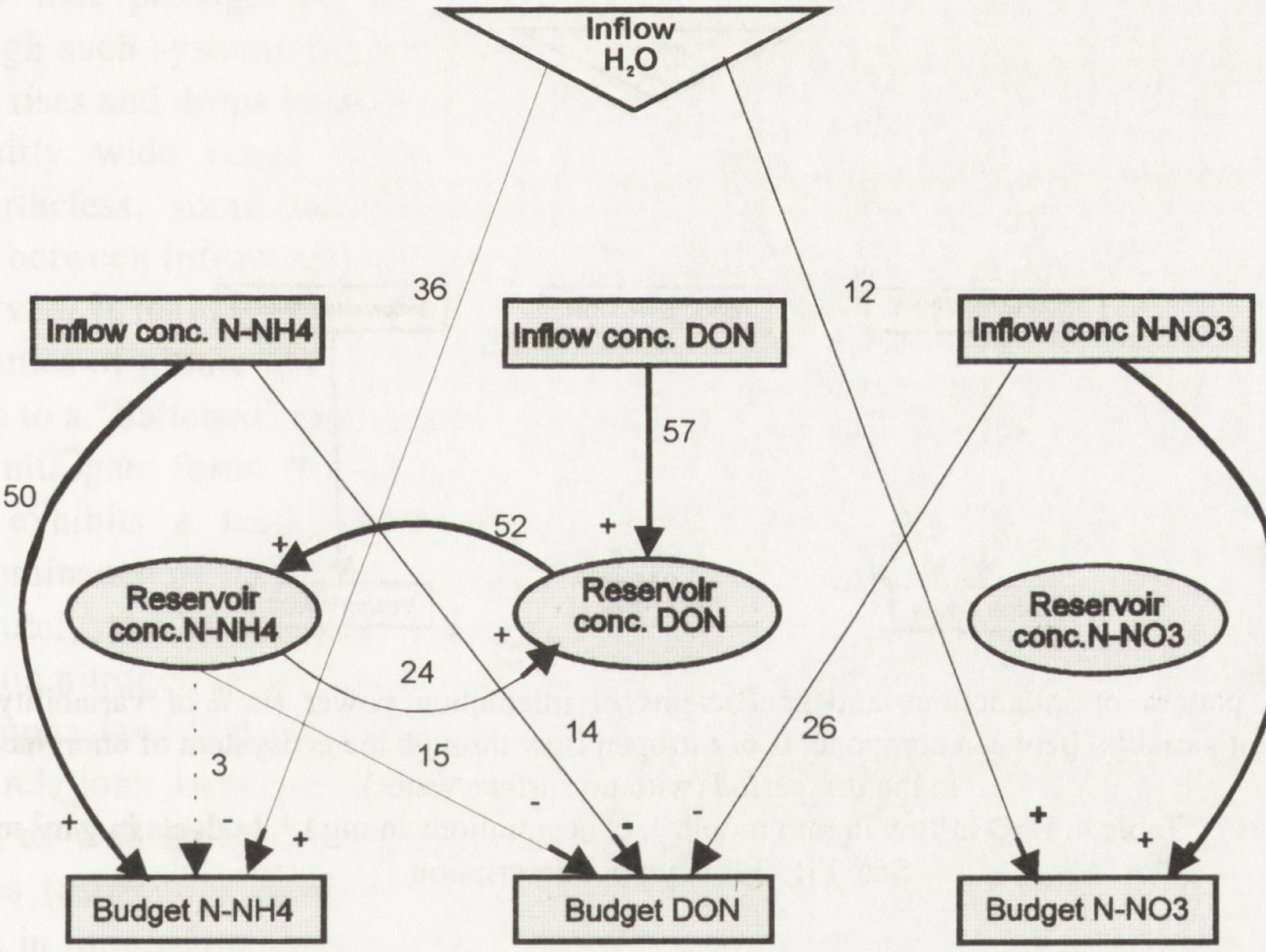

Fig. 5. A pattern of interactions and coefficients of interaction power (in % of variability of an independent variable) between components of nitrogen flow through the ecosystem of undrained fens in the wet period (with surface water). On the basis of Tables 2 and 3. H_2O inflow in mm month^{-1}, concentrations in mg l^{-1}, budgets in g m^2 month^{-1}
conc. – concentration, "+" and "-" signs denote the course of action, bold line – strong influence of a factor, dotted line – weak influence of a factor

Concentrations of nitrogen forms in surface water are poorly correlated with parameters of inflow. Only DON concentration in surface water is largely dependent upon DON concentration in inflow water (accounting for 57% of the concentration variance). Contents of DON and N-NH_4 in surface water are mutually dependent – organic nitrogen concentration explains 52% of the variance of ammonium concentration, whereas the latter parameter accounts for 24%

Table 4. Monthly budgets (inflow – outflow) of nitrogen forms flowing through undrained mire systems in the dry period (with no surface water) in g m^{-2} $month^{-1}$ (dependent variables) as functions of volume of subsurface water inflow to the mires in mm $month^{-1}$ and concentrations of nitrogen forms in that water in mg l^{-1} (independent variables)
Independent variables included after stepwise selection: Inh – N-NH_4 concentration in inflow water (mg l^{-1}), Ido – DON concentration in inflow water (mg l^{-1}), IH – volume of subsurface water inflow (mm $month^{-1}$), Ino – N–NO_3 concentration in inflow water (mg l^{-1}) (n = 16)

Budgets (inflow – outflow)	Independent variables and regression coefficients $a \pm b_1 \pm ... \pm b_n$, Significance level of b coefficient	Coefficient of determination (R^2 in %)	Significance level of R (p)
N-NH_4	–0.031 + 0.066 (Inh) – 0.034 (Ido) + 0.0005 (IH) p = 0.0002 p = 0.0032 p = 0.0074	78	$p < 0.01$
N-NO_3	–0.090 + 0.137 (Ino) p = 0.0000	90	$p < 0.01$
DON	–	0	–

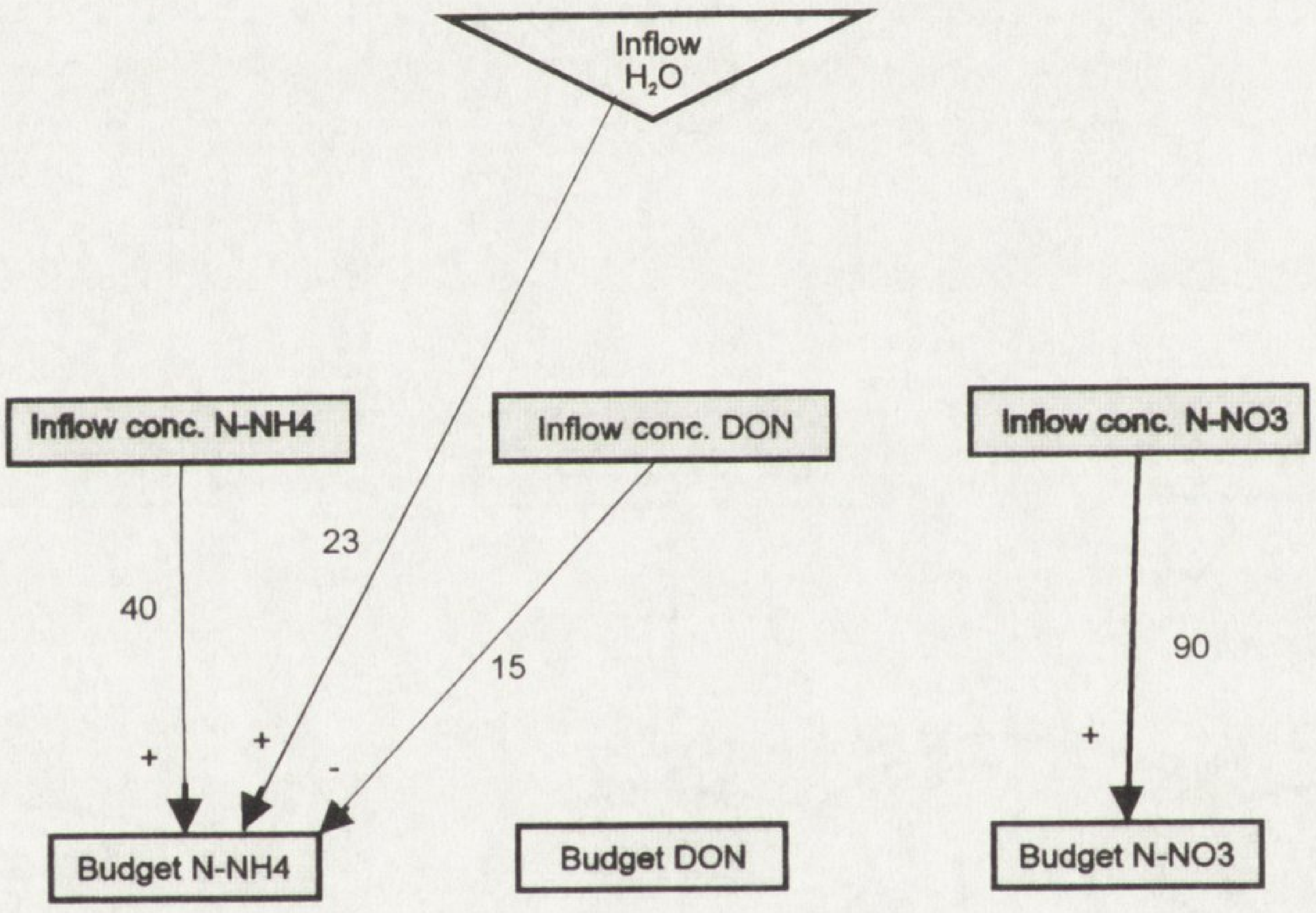

Fig. 6. A pattern of interactions and coefficients of interaction power (in % of variability of an independent variable) between components of nitrogen flow through the ecosystem of undrained fens in the dry period (with no surface water)
On the basis of Table 4. H_2O inflow in mm $month^{-1}$, concentrations in mg l^{-1}, budgets in g m^2 $month^{-1}$
See: Fig. 3 for symbol description

of DON concentration variance (Fig. 5). Concentrations of organic nitrogen in mire water are determined to a high degree by both controlling hydrochemical parameters – R^2 = 81% (Table 3). On the contrary, N–NO_3 concentration is not affected by any of the examined factors (Table 3).

During the period with no surface water (summer and autumn), the net of interactions characteristic of the flow of nitrogen forms through the mires is considerably simplified and reduced. At that time, relationships indicating a clear influence of N–NH_4 and N–NO_3 concentrations in inflow water on budgets of these ions become apparent. These parameters account for 40% of variability of ammonium budget, and for as much as 90% – that of nitrate (Fig. 6). Hydrological factor and DON concentration in inflow water play also an important role in N-NH_4 flow. Water inflow accounts for 23% of N-NH_4 budget variance, whereas DON content – for 15% (Fig. 6). Thereby, ammonium ion budget is determined to a fairly high degree by interaction of the three parameters mentioned – $R^2 = 78\%$ (Table 4). At the same time, budget of dissolved organic nitrogen in the dry period is not correlated with any of the examined parameters (Table 4).

5. DISCUSSION

Water flow through ecosystems of undrained fens situated among cultivated fields and situated at the foot of morainic hills, with very large catchment areas in relation to the wetland area is of very dynamic and unstabilized nature (Kruk 1990). These specific hydrological conditions and variability in fertilization doses cause that passage of nitrogen forms through such systems is characterized by rapid rises and drops in parameters values in fairly wide range (Figs 3 and 4). Nevertheless, some tendencies in relations between inflow and outflow may be observed. It mainly applies to a clear-cut dynamics of nitrate nitrogen inflow in relation to a "flattened" and slow outflow of that nitrogen form. Ammonia nitrogen also exhibits a tendency to periodical predominance of its inflow over outflow. Definitely, the least regular is the flow of organic nitrogen (Figs 3 and 4). It should be emphasized that the variations in mutual relations between inflow and outflow, as well as drastic changes in their values (especially those of inflow) take place in time when surface water appears or disappears. Hence, it is very important factor diversifying nitrogen flow through mires, therefore stressed in this studies.

An effect of artificial drainage of the mire No 2 was visible over one year of the studies. Enhanced outflow of N–NO_3 and drastic change in its budget – from a positive one prior to drainage to a negative one after it – is the most important effect of the measure (Table 1). What is interesting, initial increase in N-NO_3 losses with water flowing out of the mire water basin is followed by minimal outflow of that form from June till October, and considerable rise during winter (Fig. 4). Most likely, this results from nitrate uptake by plants, and then (since autumn) from intensive leaching of that ion. Nitrogen is an element easily leacheable from decaying residues of rush plants, e.g. *Typha latifolia* (Boyd 1970).

Fens located in agricultural catchments are characterized by fairly large primary production (Wilpiszewska 1990) which is, as in case of rushes, entirely returned to the ecosystem. The above phenomenon joined with an unstable hydrological system leads to rapid fluctuations of processes of mineralization and inorganic element immobilization. It also applies to mineralization of organic nitrogen into ammonium and (reversely) N–NH_4 fixation by organic matter. A convincing picture of these processes is a fairly clear relationship between those forms of nitrogen in surface water covering the mire (Table 3, Fig. 5). Moreover, effects of ammonium concentrations in both surface and inflow water on DON budget during the wet period, as well as organic nitrogen concentration in inflow water on N-NH_4 budget in the period of water deficit are clearly visible (Figs 5 and 6). As shown, the relationships change their direction depending on the season of the year. This means that under wet conditions, when oxygen is in short supply, ammonium is fixed by nitrifying bacteria (Kunicki-Goldfinger 1994) or adsorbed by humic substances (Ulehova 1971), whereas under conditions of subsurface layer aeration (summer – autumn), organic nitrogen mineralization plays more important role. Therefore, in the water-abundant period, a tendency to a relative increase in organic nitrogen outflow is outlined, while in the water-deficit period – elevated outflow of inorganic form – $N–NH_4$ comes into view.

On the background of roughly clear dependence of $N–NH_4$ and $N–NO_3$ budgets upon water inflow from the catchment area, lack of such a relationship in case of dissolved organic nitrogen budget throughout the year becomes conspicuous (Figs 5 and 6). In this context, attention should be paid to the budgets of nitrogen forms during their flow through undrained mires. It is characteristic that apart from positive budgets of inorganic nitrogen forms indicating their removing from the flow, negative budgets of DON (outflow exceeding inflow) are recorded suggesting enrichment of outflowing water with that element (Table 1). It is, therefore, possible that inorganic nitrogen is partly transformed into the organic form.

The analysis of nitrogen flow pattern (Fig. 5 and 6) reveals two reasons of the transformation discussed. First of them is an effect of $N-NH_4$ concentrations in surface water and water inflowing from the catchment on DON budget. The second one is the negative relationship between nitrate concentration in inflow water and organic nitrogen budget – the greater $N–NO_3$ inflow, the greater is relative DON outflow (Fig. 5). Presumably, intensive inflow of nitrate to the mire water basin occurring in early spring due to fertilization of fields in the catchment (Kruk 1990) is not associated with an efficient nitrate assimilation by higher plants. Nevertheless, nitrate is fixed by nitrifying bacteria (Kunicki-Goldfinger 1994). It is known that denitrification is favoured by temperatures over 5–7°C (Fotyma 1987 after Lippold et al. 1981) – a condition not always attainable in March or April. It is, therefore, possible that early spring load of $N–NO_3$ is not wholly released by microorganisms to the atmosphere, but fixed by the bacteria may then be leached to ground water as DON. The described relationships between nitrate nitrogen concentration in inflow water and organic nitrogen budget were not recorded during summer – autumn period, when nitrate inflows were lower than in spring (Table 1).

Large nitrate nitrogen input to the mires during spring due to fertilization (Figs 3 and 4, Table 1) intensifies nitrogen cycling. The pool and availability of that ion are not limited by nitrification process, as it is under natural conditions, but by an external inflow. This is the most likely reason of the lack of statistically significant relationships between $N–NH_4$ and $N–NO_3$ flows (Figs 5 and 6). Nitrate abundance in the peculiar period of spring time regrowth of vegetation results in intensification of both "assimilative" (biotic absorption) and "dissimilative" (transformation into N_2O and N_2) reduction (Wiebe et al. 1981). From the view point of biogeochemical functioning of landscape, e.g. an eutrophication effect of agricultural areas on lakes, it is important that the processes mentioned seem efficiently counteract nitrate leaching to ground water and then to lakes. Hence, the role of undrained mires as efficient barriers for inorganic nitrogen forms remains unchanged. It is only just a radical interference in the mire hydrological system – its drainage and preventing surface retention by means of artificial drainage – which eliminates the anti-eutrophication effect described.

6. CONCLUSIONS

1. Dynamics of N–NH_4 and N–NO_3 flow through undrained fens over a year period is characterized by higher loads and higher variability in inflow over outflow. The factor diversifying the properties is occurrence of surface water bodies.

2. Artificial drainage of mires results in a relative increase in nitrogen outflow, N–NO_3 in particular. This occurs mainly during winter and spring, when the drain prevents water retention typical for that period.

3. Positive budgets of N–NH_4 and N–NO_3 indicating their removal from the flow through undrained mires are controlled mainly by components of inflow of these nitrogen forms to the mires: their concentrations and volume of inflowing water.

4. A tendency to enhance DON outflow (negative budget) from undrained mires covered with water is affected by increased N–NO_3 and N–NH_4 concentrations in inflow water, as well as N–NH_4 concentration in surface water. This indicates that inorganic nitrogen is converted into the organic form.

5. Concentrations of N-NH_4 and DON in surface water are mutually dependent. At the same time, the larger amounts of organic nitrogen are derived from the catchment, the larger is its amount in the mire water basin.

6. In the period with no water at the mire surface, a balance between inflow and outflow of N–NH_4 is influenced, among other, by DON concentration in water inflowing from the catchment. This reveals the latter nitrogen form being mineralized into ammonium ion.

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7. SUMMARY

In this work, the process of nitrogen flow through mire ecosystems of fen type was subject to the analyses. This comprised investigations of flow dynamics (inflow and outflow) of nitrogen forms: N–NH_4, N–NO_3 and dissolved organic nitrogen (DON) in three different hydrological situations. Two of them concerned undrained mires, when at their surfaces water bodies occurred (winter and spring), and when for climatic reasons surface water vanished (summer and autumn). Third one referred to artificial drainage of the mire – observations were made in the year following application of the drainage. A pattern of the flow through a mire system in two hydrological situations: with the water body and without it, is presented in Fig. 1.

Two wetlands of small areas located typically for lakeland landscape in hollows with no surface run-off in catchment areas of lakes in Masurian Lakeland west of Mikołajki were assigned to the studies (Fig. 2). Vegetation cover of the sites comprised mainly rushes of cattail flag and willow shrubberies. In the soil substrate, peat and warp of slope origin occurred. Subsurface water entering the mires originated from a fertilized agricultural catchment area. By applying a range of hydrogeological methods, cross-sections of the flows were delimited. Based upon the above, hydrological parameters and nitrogen loads were determined. In order to investigate interactions between the examined factors, multiple regression was used (stepwise selection of variables and estimation of the relative importance of independent variables in predicting the dependent variable).

Presentation of the results began with a comparison of the examined parameters over a year and over the periods characterized by different hydrological conditions. In the undrained mires, particularly considerable fluctuations

were characteristic of inflows of the examined nitrogen forms. On the contrary, N-NO_3 outflows fluctuated only slightly exhibiting small loads. A range of fluctuations of N-NH_4 outflows was also smaller than that of inflows. Solely values of DON outflows were very irregular (Figs 3 and 4). After drainage, the outflow values predominated the inflow ones. The period favourable for the tendency comprised winter and spring months (Fig. 4). It turned out that all hydrological parameters were significantly different between the two periods singled out for the undrained mires – the period with the water body and without it; no differences were only found for N–NO_3 outflow indices, nor DON budget (Table 1). Budgets of nitrogen forms are altered by mire drainage. Instead of a considerable (87–97%) removal of N-NO_3 from the flow, additional quantities of that ion (budget 233%) appear in water leaving the mire. Ammonium flow is similar to that recorded in the period without a water body prior to mire drainage, and DON budget is consequently negative (Table 1).

Furthermore, the relationship in which budgets (inflow – outflow) of nitrogen forms are involved were analysed. The analysis was performed separately for the flood period and for the period without the flood. It appeared that the set of parameters describing inflow of nitrogen forms into a mire (concentrations and volume of inflowing water), as well as concentrations in surface water largely influenced budgets of nitrate forms in the wet period – determination coefficients ranged from 56 to 94% (Table 2). The analysis concerning the period considered was supplemented with examination of factors affecting concentrations of the components examined in water covering the mire. Dependence upon an external factor (concentrations in water inflowing from the catchment) occurred only in case of DON concentration in surface water. This nitrogen form is interrelated with N-NH_4 contained in surface water. In contrast, N-NO_3 concentration is not correlated with any of the examined parameters (Table 3). During the period of water deficit, budgets of inorganic nitrogen forms are determined to a high degree (R^2 = 78 and 90%) by factors constituting inflows of inorganic nitrogen forms to the mires, whereas DON budget is influenced by some other factors (Table 4).

For both wet and dry period, budgets of N–NH_4 and N–NO_3 are dependent rather on their concentrations in inflow water than on water inflow alone or other hydrochemical parameters, as is shown in the diagrams of interaction power in the process of nitrogen flow through the mire systems (Figs 5 and 6). On the contrary, DON budget during the water-abundant period seems to be a resultant of effects of nitrate concentrations in inflow water from one hand, and N-NH_4 concentrations in water inflowing and covering the mire - from the other hand (Fig. 5). This indicates that inorganic nitrogen forms are converted into the organic form under conditions of flooding. Simultaneously, during the period of water deficit, an effect of DON concentration in inflow water on ammonium budget becomes evident – DON inflow enhances N–NH_4 outflows. In contrast to the period with the water body, organic form of nitrogen is mineralized into the inorganic form.

8. POLISH SUMMARY

W pracy poddano analizie proces przepływu azotu przez ekosystemy bagien typu niskiego. Badania dotyczyły prześledzenia dynamiki przepływu (dopływu i odpływu) form azotu: N–NH_4, N–NO_3 i rozpuszczonego azotu organicznego (DON) w trzech sytuacjach hydrologicznych bagien. Dwie dotyczyły bagien niezdrenowanych, kiedy na ich powierzchni występuje zbiornik wodny (okres zimy i wiosny) i kiedy ze względów klimatycznych zanika (okres lata i jesieni) oraz sytuacji kiedy na bagnie przeprowadzono sztuczny drenaż – obserwacje obejmują pierwszy rok po tym zabiegu. Schemat przepływu przez układ bagienny w dwóch sytuacjach hydrologicznych: obecności zbiornika wodnego i przy jego braku pokazuje rys. 1.

Do badań wybrano dwa mokradła o niewielkiej powierzchni, położone typowo dla krajobrazu pojeziernego w zagłębieniach powierzchniowo bezodpływowych w obrębie zlewni jezior na Pojezierzu Mazurskim na zachód od Mikołajek (rys. 2). Szatę roślinną tych obiektów stanowił głównie szuwar pałki szerokolistnej, a także zarośla wierzbowe. W podłożu występował torf i namuł pochodzenia zboczowego. Wody podpowierzchniowe dopływały do bagien z nawożonej zlewni rolniczej. Wykorzystując szereg metod hydrogeologicznych wytyczono przekroje przepływu tych wód, a na tej podstawie parametry hydrologiczne i ładunki przepływu form azotu. Aby wniknąć w zależności pomiędzy badanymi czynnikami skorzystano z metodyki analizy regresji wielokrotnej (krokowa selekcja zmiennych i ocena siły wpływu zmiennych niezależnych na zmienną zależną).

Prezentacje wyników rozpoczęto od przedstawienia i porównania wielkości badanych parametrów w cyklu rocznym i wydzielonych okresach różnych warunków hydrologicznych. Na bagnach niezdrenowanych dużą dynamiką zmian odznaczają się zwłąszcza dopływy badanych form azotu. Natomiast szczególnie odpływy $N\text{–}NO_3$ mają łagodny przebieg przy małych wartościach ładunków, odpływy $N\text{–}NH_4$ również odznaczają się mniejszym zakresem zmian niż dopływy i tylko odpływy DON mają bardzo nieregularny charakter (rys. 3 i 4). Po zdrenowaniu większe wartości osiągają odpływy niż dopływy, a okresem najbardziej sprzyjającym tej tendencji są miesiące zimowe i wiosenne (rys. 4). Okazało się, że wszystkie parametry hydrologiczne i większość biogeochemicznych różnią się istotnie statystycznie w obu okresach charakteryzujących bagna niezdrenowane – ze zbiornikiem i bez; różnic nie stwierdzono jedynie dla wskaźników odpływu $N\text{–}NO_3$ i bilansu DON (tab. 1). Wartości bilansów form azotu ulegają zmianie po zdrenowaniu bagna. Zamiast znacznego (87–97%) wyłączania z przepływu $N\text{–}NO_3$ pojawiają się teraz w odpływie jego ilości dodatkowe (bilans – 233%). Przepływ azotu amonowego jest podobny jak w okresie nieobecności zbiornika wodnego przed drenażem, a bilans DON jest konsekwentnie ujemny (tab. 1).

Następnie przeanalizowano zależności jakim podlegają bilanse form azotu (dopływ–odpływ). Analizę przeprowadzono osobno dla okresu występowania zbiornika wodnego na bagnie i jego braku. Okazało się, że zestaw parametrów charakteryzujących dopływ form azotu do bagien (stężenia i wielkóści dopływu wody), a także stężenia w zbiorniku wodnym silnie determinują bilanse form azotu w okresie obfitości w wodę współczynniki determinacji wynoszą od 56 do 94% (tab. 2). Analizę z tego okresu usupełniono o znalezienie czynników kształtujących wartości stężeń badanych składników w zbiornikach bagiennych. Uzależnienie od czynnika zewnętrznego (stężenia w wodach dopływu ze zlewni) występuje jedynie w przypadku stężenia DON w zbiorniku. Forma ta razem z $N\text{–}NH_4$ tworzy w wodach zbiornika układ wzajemnej zależności. Natomiast stężenie $N\text{–}NO_3$ nie jest skorelowane z żadnym z badanych parametrów (tab. 3). W okresie z deficytem wody bilanse form nieorganicznych są silnie zdeterminowane (R^2 = 78 i 90%) przez dopływy tych form azotu do bagien, natomiast bilans DON kształtują inne niebadane czynniki (tab. 4).

Jak pokazują schematy zależności elementów przepływu azotu przez systemy bagienne (rys. 5 i 6) zarówno w okresach ze zbiornikiem wodnym, jak i bez niego, bilanse $N\text{–}NH_4$ i $N\text{–}NO_3$ silniej zależą od stężen tych form w dopływie ze zlewni niż od wielkości dopływu wody i innych czynników hydrochemicznych. Z kolei bilans DON w okresie obfitym w wodę wydaje się być wypadkową oddziaływania z jednej strony stężeń $N\text{–}NO_3$ w dopływie, a z drugiej stężeń $N\text{–}NH_4$ w dopływie i w zbiorniku wodnym (rys. 5).Świadczy to o przemianie form nieorganicznych azotu w organiczną w warunkach podtopienia. Jednocześnie w okresie deficytu wody zaznacza się wpływ stężenia DON w dopływie na bilans jonu amonowego – dopływ DON zwiększa odpływ $N\text{–}NH_4$. Odwrotnie do okresu ze zbiornikiem, teraz forma organiczna azotu ulega przemianie na drodze mineralizacji w składnik mineralny.

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