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Marek KRUK

Department of Plant Ecology, Institute of Ecology, Polish Academy of Sciences, Dziekanów Leśny (near Warsaw), 05-092 Łomianki, Poland

THE PROCESSING OF ELEMENTS BY MIRES IN AGRICULTURAL LANDSCAPE: MASS BALANCES BASED ON SUB-SURFACE HYDROLOGY*

ABSTRACT: Small mires located in hollows with no surface outflows were subject to biogeochemical studies by input-output balance method based on measurements of groundwater flows. Estimates were made of water balance as well as balance of dissolved forms of: N (including $N-NO_3$, $N-NH_4$, $N_{org.}$), K, Na, Ca, Mg, $S-SO_4$ and Cl. The following undrained mires were examined: two with minerotrophic fen and one with ombrotrophic-transition bog. Also a drained minerotrophic mire was studied. It was observed that nitrogen outflow from undrained mires was considerably smaller. The mire with ombrotrophic-transition bog could retain a substantial part of a scanty inflow of the examined elements, while mires with minerotrophic fen – upmost a tiny part of a rich inflow mainly from catchment basin. Drained minerotrophic mire was no longer apt to retain a majority of elements, nitrogen in particular.

KEY WORDS: Elements, mires, inflow, outflow, drainage, ground water flow.

1. INTRODUCTION

Mires rank among systems of unpoised, positive balance of matter (Moore and Bellamy 1974). In a landscape subject to weathering processes and water transportation, these are places where matter may remain temporarily excluded from cycling. In the process of their development peatlands retained considerable amounts of mineral elements (Malmer and Sjörs 1955, Morsjö 1968, Sonnesson 1970, Damman 1978, Waughman 1980). On the other hand, mires number among more or less transmissional systems.

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The present studies aimed at determining a proportion between the part of matter remaining in a mire and that leaving it, i.e. estimate of element balance in a mire. The studies examined the following nutrients: nitrogen, potassium, sodium, calcium, magnesium, sulphur and chlorine. The method employed was that for examining land components of balance with regard to groundwater flows.

The most basic genetic classification of peatlands was observed in the present work, namely, into minerotrophic, ombrotrophic and transition types (Moore and Bellamy 1974). The first type comprises mires whose main feeding source is water inflowing from catchment basin, the second type – mires predominantly fed by atmospheric water, while the last type includes peatlands which are only partly fed by inflow from land. The main feeding source as a criterion for peatland classification was first employed by Kulczyński (1941/1942). The following types of mires: soligenic and minerotrophic, i.e. the rich ones, and ombrogenic and ombrotrophic, i.e. the poor ones, were distinguished by numerous authors (Sjörs 1950, Du Rietz 1954, Gorham 1967, Heinselman 1970).

The specific traits of the mires examined in the present studies are as follows: small area, location amidst ploughlands, the lack of watercourse inflow and outflow and the occurrence of periodic water bodies. One of the attempts of the present work was to reveal main features of element processing by these systems of impeded outflow, so very frequent in a lake district landscape, as well as their comparison to biogeochemical properties of a mire directly after drainage.

Biogeochemical properties of small, mid-ploughland mires have only recently focused attention of ecologists (Warncke 1980, Verhoeven et al. 1983, Comeau and Bellamy 1986, Wilpiszewska 1990). The significance of undrained mires in element cycling on agricultural areas is implicitly pointed to by a distinct dependence between catchment area characteristic of mires and trophic status of their water (Kruk 1988b).

Balances of mineral elements in the studied mires are based on water balances. Most water balances of peatlands provided in literature concern either raised bogs (Ivanov 1953, 1957, Morrison 1955, Romanov 1961, Eggelsmann 1971, Burke 1975a, De Smedt et al. 1977) or complexes of drained swamps (Orsztynowicz 1963, Bavina 1966). Also the balances of elements in peatlands worked out theretofore applied either to swamp along with its catchment area or to bogs with a surface outflow (Crisp 1966, Burke 1975a, Helmond 1980, 1983, Warncke 1980, Verry and Timmons 1982). Ground inflows and outflows of elements on peatlands have been studied moreover as accompanying components. Several authors called for quantitative estimates of groundwater flow in peatlands (Moore and Bellamy 1974, Gosselink and Turner 1978, Gorham 1982, Ingram 1983).

In the present studies an attempt was made to define element balance in mires by method of underground flow measurements. The occurrence of mires in hollows with no surface run-off imposes peculiar conditions on water flow, unlike those in watercourse watersheds. Water flow in the former depends on diversified filtration properties of undrained peat (Rycroft et al. 1975), as well as periodical, forced by impeded outflow occurrence of surface water bodies.

An interesting issue tackled in the present work is, among others, a seasonal aspect of nutrient processing in mires. Is "vegetation pump" in vegetative season the only mechanism checking the outflow of elements from peatlands (Prentki et al. 1978).

An attempt was also made in the work to evaluate the effect of mires on element movement from agricultural areas to the lake zone. The question if natural peatlands trap nutrients translocating in watershed has already interested other authors (e.g. Surakka and Kamppi 1971, Toth 1972, Lee et al. 1975, Richardson et al. 1976, Prentki et al. 1978).

2. THE SITE OF STUDIES

The site assigned for the present studies is situated west of the locality of Mikołajki, comprising a plot of Masurian Lakeland, mainly under agricultural use (Fig. 1). Its geographical location is 21°30′ E; 53°50′ N.

The environs of Mikołajki have moderate transition climate, yet they are also affected by continental climate, as implied by 2–3°C lower mean annual temperature (6.5°C), its greater annual amplitude, shorter vegetative season and snowier and frostier winters (Bajkiewicz-Grabowska 1985). Precipitation characteristics in the two years of studies differed considerably. In the period of May 1982–April 1983, the amount of precipitation was 614.8 mm, but only 367.0 mm in the next year.

The study site represents a lay-out of relief of the earth surface typical of lakeland landscape. Quite a vast area is occupied by moraine plateau with irregular knob-and-kettle topography, full of numerous dead ice depressions partly filled up with peatlands. The plateau is broken up by a glacial through with two larger lakes, Jorzec and Głębokie, as well as by a broad dead ice depression with the Inulec Lake. The Jorka river, a man-made water course, flows through the lake system (Fig. 1).

On the area of the Masurian Lakeland there may be found minerotrophic, transition as well as ombrotrophic peatlands. The location of ombrotrophic and transition peatlands in water-parting zones (e.g. B area on Fig. 1), and the occurrence of marginal zones bordering on mineral soils cause their indepence of water of the surrounding areas (Kruk 1988a). Considerably more numerous on the Masurian Lakeland are minerotrophic mires, occupying a tiny part of their watershed systems.

The size of peatlands on the study site was fairly diversified. The greatest peatland with no surface run-off had an area of about 26 ha, while the area of the smallest mires ranged from 0.02 to 0.10 ha. The prevailing were mires whose area did not exceed 0.2 ha (Kruk 1988a).

Land use on the study site was predominantly agricultural (Table 1). Crop lands occupied the greatest area, smaller area was covered by grasslands spreading on

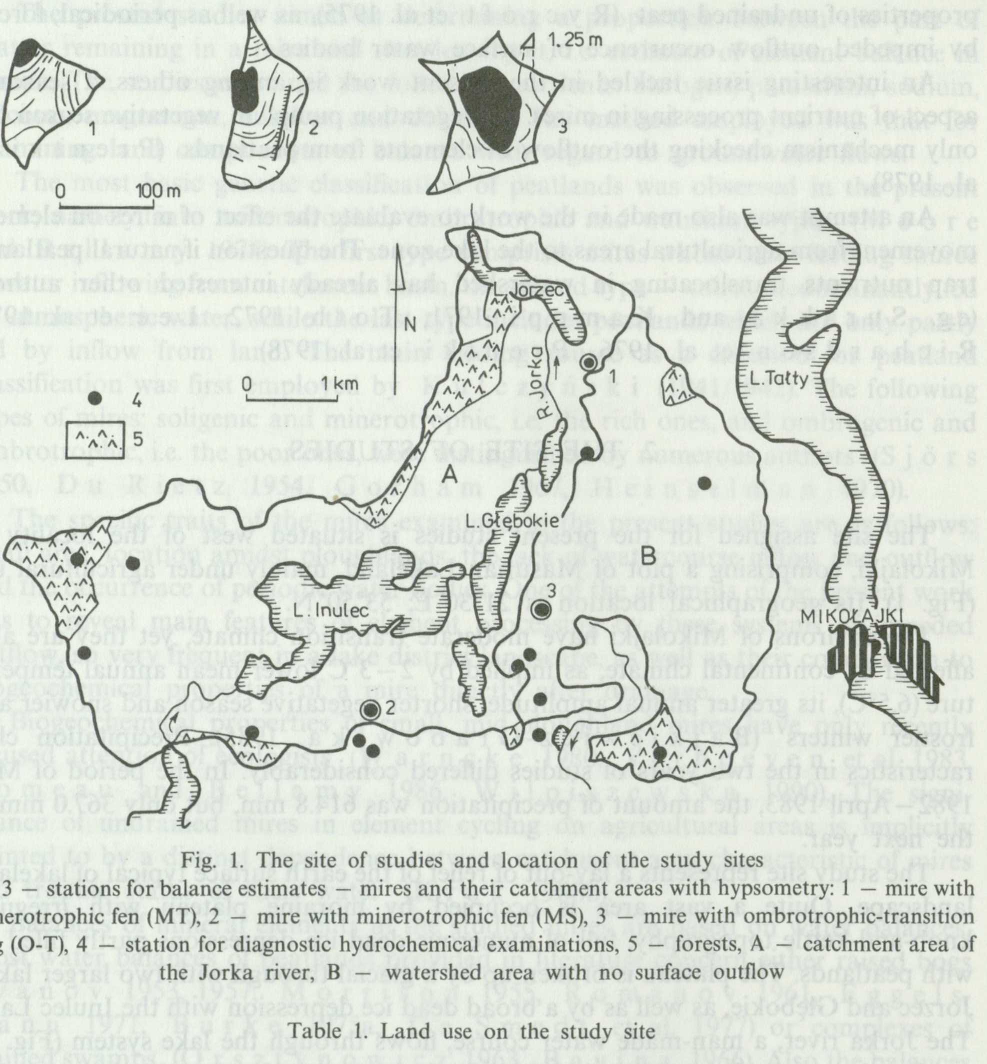

Fig. 1. The site of studies and location of the study sites
1–3 – stations for balance estimates – mires and their catchment areas with hypsometry: 1 – mire with minerotrophic fen (MT), 2 – mire with minerotrophic fen (MS), 3 – mire with ombrotrophic-transition bog (O-T), 4 – station for diagnostic hydrochemical examinations, 5 – forests, A – catchment area of the Jorka river, B – watershed area with no surface outflow

Table 1. Land use on the study site

Type of land use	Area (ha)	Contribution to the total area (%)
Crop fields	1319.2	44.9
Grasslands on mineral soil	333.9	11.4
Grasslands on organic soil	245.9	8.4
Forests	438.2	14.9
Water bodies	312.0	10.6
Unused waterlogged areas, including:	225.2	7.7
mires on ploughland	170.2	5.8
Others	65.3	2.1
Total	2939.7	100.0

mineral and organic soils (Table 1). Forests — mostly pine-spruce woods — clustered in three larger complexes (Fig. 1). Most marshy lands on the studied site comprised mires with natural vegetation, located in hollows with no surface outflow and surrounded by ploughlands (Table 1).

Mires spreading amidst arable lands were grown with diversified swamp vegetation. In about 50% of swamps the dominating were willow shrubberies, whereas in about 5—10% the prevailing were alder swamps, reed and sedge fens, *Sphagnum* bogs with associations characteristic of transition bogs, raised bogs and bog pine woods (Kloss and Wilpiszewska 1985). Fairly numerous were also little ponds with associations of floating plants. Most marshes spread on swampy soil — peat and swampy mud soil.

Crop fields were situated on brown soils formed of loams and loamy sand, while meadows — on peat muck soil. Mineral fertilization of ploughlands amounted to (in net component): 56—100 kg N·ha^{-1}, 17—45 kg P·ha^{-1} and 98—114 kg K·ha^{-1}, whereas that of grassland 65 kg N·ha^{-1} and 10 kg P·ha^{-1} (Traczyk et al. 1985).

Three mires located amidst ploughlands in hollows with no surface run-off were assigned for detailed studies (Fig. 1). The chosen sites represented a wide range of hydrological and trophic properties typical of lakeland landscape — the mires had a contrastively different relative size of watershed (Fig. 1).

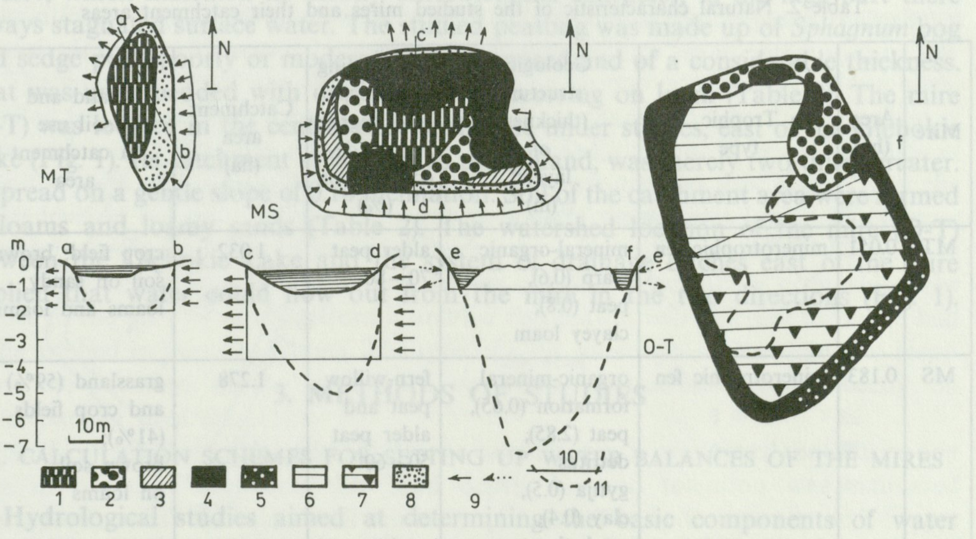

Fig. 2. Vegetation cover of the mires with minerotrophic fen (MT and MS) and of the mire with ombrotrophic-transition bog (O-T) and their hydrogeological situations
1 — Typhetum latifoliae, 2 — Caricetum elatae, Caricetum vesicariae, 3 — Acoretum calami, 4 — Salicetum pentandro-cinereae, 5 — community with *Alnus glutinosa*, 6 — *Sphagnum* bog with *Oxycoccus sphagnetea*, *Vaccinium uliginosum* and *Carex lasiocarpa*, 7 — *Sphagnum* bog with *Carex lasiocarpa* grown with *Betula pubescens*, 8 — meadow community of the class Molinio-Arrhenatherea, 9 — inflow and outflow directions of subsurface water (permanent and temporal), 10 — bottom limit of hydrologically active layer of mires in cross-section, 11 — limit of peat deposit in cross-section

Here is a short natural characteristic of the chosen study sites:

1. Mire with minerotrophic fen (with Typhetum latifoliae) (MT). In this small mire of merely 510 m^2 in area two parts could be distinguished, namely, a larger one (310 m^2), grown with association of cattail (Typhetum latifoliae Soo 1927), and a smaller one, encompassing the cattail association on one side with a wet and unmown meadow of the class Molinio-Arrhenatheretea R. Tx. 1937 (Fig. 2). It was usually the cattail plot that was temporarily flooded. The basement soil comprised a layer of an alluvial origin – clayey-silty warp with layers of organic matter. Below there was a layer of strongly decomposed lowmoor peat occurring directly on boulder clay (Table 2). The mire (MT) was found in the northern part of the site under studies, south-east of the Jorzec Lake (Fig. 1). It spread under the slope of glacial through, yet about 4 m over depositional terrace of the lake. The catchment area of the mire comprised mainly the slope of the through of up to 0.25 inclination and was under agricultural use (ploughland). Its soil was made up of sandy loam in the surface layer and of loam underneath (Table 2). In summer there were observed on the catchment area traces of surface washing and accumulation of slope material, which, however, never reached the mire border. The catchment area was several times larger than that of the mire (Table 2).

2. Mire with minerotrophic fen (with Salicetum pentandro-cinereae) (MS). The mire of 1830 m^2 in area was made up of some plots of marshy vegetation. The

Table 2. Natural characteristic of the studied mires and their catchment areas

Mire	Area (ha)	Trophic type	Geological structure (thickness of layers) (m)	Dominating peat type and degree of its decomposition (%)	Catchment area (ha)	Land and soil use in catchment area
MT	0.051	minerotrophic fen	mineral-organic warp (0.6), peat (0.8), clayey loam	alder peat 70–80	1.032	crop field; brown soil on sandy loams and loams
MS	0.183	minerotrophic fen	organic-mineral formation (0.65), peat (2.85), detritus gyttja (0.5), clay (0.4), sandy loam	fern-willow peat and alder peat 50–60	1.278	grassland (59%) and crop fields (41%); brown soil on loams
O–T	0.492	ombrotrophic-transition bog (minerotrophic marginal part)	peat (7.0), detritus gyttja (0.5), loam	sedge-moss fen peat, transition bog peat, raised bog peat 20–30	1.068	crop field; brown soil on sandy loam and loams

greatest area (about 40%) was grown with willow shrubberies (Salicetum pentandro-cinereae (Almq. 1929) Pass. 1961) (Fig. 2). In time of spring thaws almost the whole mire area was flooded. The surface layer was formed of peat with an admixture of clayey-silty material. Below there occurred lowmoor, mostly sedge, peat, moderately decomposed underbedded with detritus gyttja and clay (Table 2). The mire (MS) was located in the southern part of the site under studies about 800 m south of the Inulec Lake (Fig. 1). The inclination of the catchment area slopes approximated 0.20, the catchment area being considerably vaster than the mire itself. Soil of the catchment area was made up mainly of loams and were used as ploughland and grassland (Table 2). On the slope where a crop field spread there were observed local (not reaching the mire) traces of surface washing. After about a year the studies had been started, an artificial drainage of the mire began. A drain pipe installed at the depth of 0.7 – 1.0 m dewatered the surface layer of the mire, directing water to the Inulec Lake.

3. Mire with ombrotrophic-transiton bog (O-T). Within 4920 m^2 of the mire area, the following phytocoenoses were distinguished: *Sphagnum* bog with *Oxycoccus quadripetalus* Gilib. and *Vaccinium uliginosum* L. (ombrotrophic) and *Sphagnum* bog with *Carex lasiocarpa* Ehrh., grown mainly with *Betula pubescens* Ehrh. (transition) (3320 m^2 in total) in the central part of the mire and on the mire lagg – a minerotrophic fen composed mainly of willow shrubberies (Salicetum pentandro-cinereae (Fig. 2). The area of *Sphagnum* bog was not flooded during the time of studies, which indicated its mostly ombrotrophic character; in the lagg part there always stagnated surface water. The studied peatbog was made up of *Sphagnum* bog and sedge peat, poorly or moderately decomposed and of a considerable thickness. Peat was underbedded with detritus gyttja occurring on loam (Table 2). The mire (O-T) was located in the central part of the site under studies, east of the Głębokie Lake (Fig. 1). Its catchment area, used as ploughland, was merely two times greater. It spread on a gentle slope of 0.10 inclination. Soil of the catchment area were formed of loams and loamy sands (Table 2). The watershed location of the mire (O-T) between the Głębokie Lake and the system of drainage ditches east of the mire implied that water could flow out from the mire in the two directions (Fig. 1).

3. METHODS OF STUDIES

3.1. CALCULATION SCHEMES FOR SETTING UP WATER BALANCES OF THE MIRES

Hydrological studies aimed at determining the basic components of water balances in the three chosen mires. Water balances of the mires with minerotrophic fen and of that with ombrotrophic-transition bog were estimated applying different procedures.

Water balance of the mires with minerotrophic fen were calculated from the following formula:

$$I_g + P = O_g + \Delta R(g + s) + ET$$

where: I_g — ground inflow, P — precipitation, O_g — ground outflow, $\Delta R(g+s)$ — retention difference (ground and surface), ET — evapotranspiration.

Hydrogeological conditions of the studied mires with minerotrophic fen were marked for the occurrence of inflow and outflow zones of ground water (Fig. 2) and for the occurrence of hardly permeable layer underlying the peat layer (Table 2). This allowed for calculating ground inflow and outflow on the basis of Darcy's law (Pazdro 1983):

$$I_g, O_g = k \cdot a \cdot s$$

where: k — hydraulic conductivity, a — cross-sectional area, s — slope of water table (hydraulic gradient).

The studied peatland layer bottomed in the inflow and outflow zones by unpermeable formation (clay or clayey loam) may be defined as a hydrologically active layer of the mire (Fig. 2).

Drainage outflow from minerotrophic mire (MS) was estimated after Kostjakov method (1960) with regard to a drain pipe fixed in the waterbearing layer and functioning in one way, i.e. from the mire onwards (Fig. 3). In the period when water table in mire was beneath drain pipe — Darcy's low was employed.

In water balance of the mire after drainage there was disregarded a vehement outflow of water directly after the drain pipe was put into use (the outflow of surface water lasted about 10 days). Data on the amount of precipitation was taken from the weather station in Mikołajki, situated 5.0—6.5 km from the sites under studies.

Surface retention of the mire was estimated as follows. In case of the mire (MS) the surface water basin was compared to a spherical sector of a constant smaller

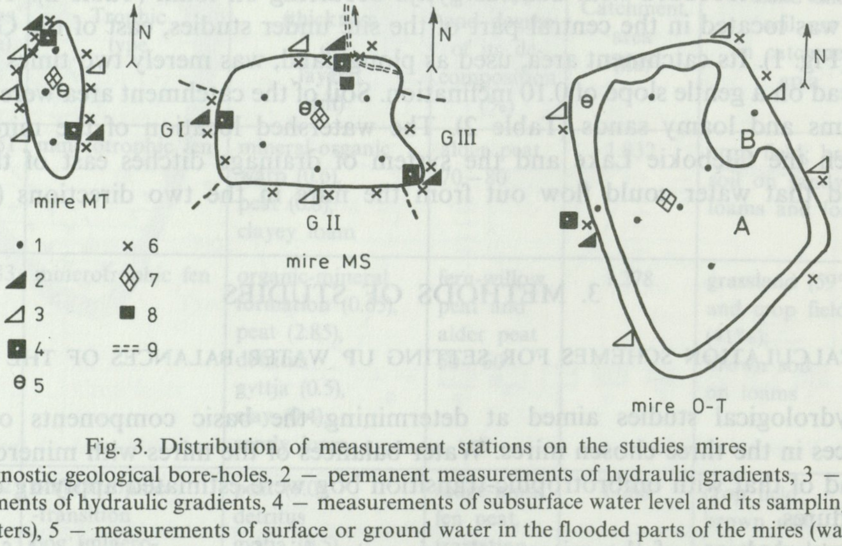

Fig. 3. Distribution of measurement stations on the studies mires
1 — diagnostic geological bore-holes, 2 — permanent measurements of hydraulic gradients, 3 — control measurements of hydraulic gradients, 4 — measurements of subsurface water level and its sampling stands (piezometers), 5 — measurements of surface or ground water in the flooded parts of the mires (water level indicators and piezometers), 6 — measurements of hydraulic conductivity of mineral grounds, 7 — measurements of hydraulic conductivity of peats and mineral-organic deposits, 8 — water sampling stand in outflow zone of the mire (MS) after installing drain, 9 — drain pipe, GI, GII, GIII — sub-catchment areas of the mire (MS), A — central part of the mire (O-T), B — lagg of the mire (O-T)

radius of a sphere section corresponding to the central part of the mire and of variable larger radii depending on the flood range (the formula after Bronsztejn and Siemiediajew 1970). For the mire (MT) surface retention was calculated as a product of the basin area and its depth. Ground retention in the hydrologically active layer of the mires was identified with the volume of free ground water in this layer. The volume was estimated on the basis of the mire area, the height of the ground water level over the bottom limit of the hydrologically active layer and desaturation index of formations making up this layer. Desaturation index of peat was calculated from Iwicki's equation ($\mu_p = 8.2 \sqrt[8]{k^3} \sqrt[4]{H^3}$, where: k – hydraulic conductivity, H – thickness of desaturated stratum) (Ostromęcki 1960). Desaturation indices (μ_m) of mineral grounds were counted after Biecinski's equation ($\mu_m = 0.117 \sqrt[7]{k}$, where: k – hydraulic conductivity) (Wieczysty 1982).

Evapotranspiration along with other unmeasured elements (e.g. budget of retention in the aeration zone, budget of water exchange throught the mire bottom, snow-drift or fog precipitation) were calculated from the balance equation.

Water balance of the mire with ombrotrophic-transition bog was estimated after two formulae applied alternately:

$$I_g + P = \Delta R(g + s) + ET_p \qquad (1)$$

$$\text{or } P = O_g + \Delta R(g + s) + ET_p \qquad (2)$$

where: ET_p – potential evapotranspiration, other symbols – see the balance formula for the mires with minerotrophic fen.

The employment of one of the above formulae for one estimate period (a month) resulted from a specific type of water cycling in the examined mire. In the course of observation of water level around the mire it turned out that in certain periods of time the level of free ground water in the mire surroundings was higher than the water level in the mire, whereas in other periods of time it was lower. The former situation would imply an inflow of water to the mire and the latter – its outflow (Fig. 2). Hence it may be concluded that in certain periods there occurred either inflow to the mire or outflow from it and for this reason two different formulae had to be applied in the calculations. The type of such water cycling was likely to result from the location of the mire with ombrotrophic-transition bog directly on water-parting area (Fig. 1).

Surface retention of the mire (O-T) was calculated as a product of the water body area in the mire lagg and the flood depth. Ground retention was estimated analogically as for the mires with minerotrophic fen. The hydrologically active layer was indirectly determined. The height of this layer approximated mean depth of surface water body in the mire lagg in a given estimate period (Fig. 2).

Quantity of evapotranspiration on the mire (O-T) was calculated as the amount of potential evapotranspiration after Turc's equation (Pleczyński 1978). The area of the mire with ombrotrophic-transition bog was constantly waterlogged (*Sphagnum* bog) or flooded under shrubs shelter (the lagg zone). An approximate quantity of evapotranspiration from such areas equals the amount of potential evapotranspiration (Ivanov 1953, Bavina 1966).

The amounts of ground inflow or outflow for the mire (O-T) were therefore calculated from a balance equation made up of the values of precipitation, potential evapotranspiration and changes in mire water retention (estimated on the basis of changes in water level). A positive result of balancing these elements stood for the amount of inflow, whereas a negative one – for outflow.

It was assumed in hydrogeological studies of mires that desaturation indices of peats and mineral grounds adjoining peats were not indicative of unpermeability of these formations, yet the occurrence of hydraulic gradient between water in these formations proved underground water flows.

Due to various agricultural use of catchment area of the mire with minerotrophic fen (MS), it was divided into three partial watersheds, out of which inflows to the mire were estimated separately (Fig. 3). The studies were conducted for two years. Values of the components of water balance of the mires were expressed in terms of monthly and yearly values.

3.2. MEASUREMENT OF HYDROGEOLOGICAL PARAMETERS

In order to estimate the amount of ground water inflow and outflow in the mires as well as the value of ground retention, the following hydrogeological parameters had to be measured: lengths and rises of water flow sections, hydraulic gradients (slopes of water table) and coefficients of hydraulic conductivity of the studied grounds.

The length of inflow and outflow zones on the mires were estimated on the basis of control measurement results of differences in mire water levels and in several bore-boles on mire surroundings (Fig. 3). The differences were measured by geodetic theodolite (produced by Carl Zeiss Jena).

In order to estimate the rises of water flow sections on the mires with minerotrophic fen, a number of geological drilling were made on their premises (Fig. 3). Hence the depth at which hardly permeable layers occurred was defined in particular inflow and outflow zones and, consequently, the bottom limit of flow sections i.e. of mire hydrologically active layer, was determined. Rises of flow sections in mire zones in particular months were counted on the basis of measurements of water level in piezometers installed in these zones (Fig. 3). The length of zone multiplied by the rise of ground water flow sections gave in result the area of section of water flow to and from the mire.

Hydraulic gradients were calculated on the basis of differences between the results of measurements of water levels taken with geodetic theodolite. In inflow zones of the mires with minerotrophic fen differences in water level accounted for the difference between the water level in piezometer in this zone and the surface water level or the water level in piezometer situated in the center of the mire (Fig. 3). Hydraulic gradients of water flowing out of the mires with minerotrophic fen were measured on the basis of differences in water levels between piezometers in outflow zones and the water levels in water bodies situated beneath the studied mires.

Coefficients of hydraulic conductivity which were to define inflows and outflows of water on the mires, were actually measured outside the mires – in lower parts of mire catchment area as well as in and below the outflow zone (one measurement in 5–10 m of mire perimeter) (Fig. 3). Mean coefficient of hydraulic conductivity was estimated for each zone. Measurements of hydraulic conductivity coefficient in mineral grounds around the mire were taken after auger hole Pisarkov's method (Wieczysty 1982), based on measurements of the rate of the rise of lowered water level in a borehole. The product of the area of water flow section, the value of hydraulic gradient and the value of hydraulic conductivity coefficient gave the amount of underground flow of water (Pazdro 1983), i.e. of inflow or outflow from mire.

Coefficients of hydraulic conductivity of peats and clayey-peat layers required for estimates of desaturation indices of these formations were determined on the basis of observations of the rise of artificially lowered water level in a bore-hole – Erkin formula (Romanov 1961). The measurements were taken in central parts of the studied mires (Fig. 3). Desaturation indices were made use of in determining the value of mire ground retention.

3.3. SAMPLE COLLECTION

Samples for chemical analyses of underground water flowing in and out of the mires with minerotrophic fen were taken from piezometers installed in inflow and outflow zones on the mires (Fig. 3). In the mire (MT) there was established one station of constant water sampling in the inflow zone and one in the outflow zone, whereas in the mire (MS) – two stations in the inflow zone and one in the outflow zone (Fig. 3). One station under the catchment area of the mire (MS) supplied samples of water inflowing from under ploughland, while the other – from under grassland on mineral soil (partial watersheds G I and G III on Fig. 3). Concentration of elements in water inflowing from the watershed under a mixed use (G II), where 50% of the area is occupied by ploughland and the other 50% by meadow, was a mean of concentration values of water from the stations under the neighbouring partial watersheds.

Water samples for determining concentration of elements in water inflowing to the mire with ombrotrophic-transition bog (O-T) were taken from a piezometer installed about 4 m off the mire boundaries. Concentration of elements in water flowing out from the mire was estimated on the basis of surface water samples taken on the mire lagg in the periods of water outflow from the mire. Concentration of nutrients in water outflowing by the drain pipe and hydrologically active layer below from the drained mire (MS) was counted from the samples of water flowing through the drain pipe and those taken from the outflow zone 2–4 m from the drain, i.e. on a strongly drained area (Fig. 3).

Samples of ground and surface water in the three mires under studies were collected once a month, directly after hydrological measurements were taken. Underground water samples were obtained by emptying piezometers made of PCV pipes 15 cm diameter and perforated at the bottom at a length of 50–80 cm. Piezometers reached down to 60–100% of thickness of hydrologically active layers in particular mires. Before a sample was taken, piezometers were emptied of water they contained, and only after subsequent refilling 3–5 l water samples were scooped out of them. Water samples were then poured through nylon mesh to a polyethylene canister of 5 l volume. Side by side regular sampling, also a series of test samples was taken from 2–3 stands in the inflow and outflow zones of the studies mires. They served as a basis for determining statistical variation of nutrient concentrations in various places in mire inflow and outflow zones.

In order to define chemical properties of mire water in the environs of Mikołajki a single sampling was additionally performed of water from nine minerotrophic and six ombrotrophic and transition peatlands (Fig. 1). Element concentration in ground water of mires with minerotrophic fen was estimated from the samples taken in 2–3 stands located on the mires. Element content in ground water of hydrologically active layer equalled the mean of their content in the sampling stations.

Data on the content of elements dissolved in rain water (in $\mathrm{mg \cdot l^{-1}}$) were taken from unpublished materials by J. R. Zimka and A. Stachurski (methods described in works: Stachurski and Zimka 1982, 1984). The station for collecting precipitation samples was situated 1–5 km from the mires examined in the present studies.

3.4. CHEMICAL ANALYSES

The ground and surface water samples were filtered through GF/F Whatman filter paper of 1 μm mesh a few hours after sampling. After about 24 h, a part of water (about 200 ml) was subject to pH and electroconductivity denotations in laboratory and was subsequently poured into gravimetrically determined little evaporating dishes (two in a sample) and weighed. Next water was evaporated in a drier at 60°C and evaporating dishes with deposit after evaporation were weighed on "Sartorius" analytical balance. Thus the weight of deposit after evaporation was obtained. Then the content of deposit in 1 l of water calculated. The remaining part of water (3–5 l) was poured in portions into 0.5 l evaporation dishes which were subsequently placed in a drier and dried at 60°C up till all the water samples were evaporated. Then deposit was removed from evaporating dishes and homogenized. An alike method of measuring deposit content and procedure of its asquisition was employed for about a 1 l sample of water to which 1–2 mg of salicylic acid were added thus reducing the solution pH down to less than 3. Deposit obtained thereby served for denoting elements and their forms (Stachurski and Zimka 1984).

Total nitrogen was denoted on CHN gas chromatograph produced by Carlo Erba. Denotations were made in samples of deposit with salicylic acid, which was used so as to impede the release of ammonia during evaporation in the process of obtaining deposit from water samples. A standard deposit sample weighed about 1 mg. Total nitrogen concentration was calculated by multiplying the content of deposit after evaporation in 1 l of water by percentage content of nitrogen in the deposit (Stachurski and Zimka 1984). The content of ammonium nitrogen was calculated by subtracting from total nitrogen content the content of nitrogen denoted on autoanalizer in a sample without salicylic acid, i.e. under conditions favouring transition of ammonium ion into gaseous phase (NH_3) (Stachurski and Zimka 1984). Concentration of nitrate nitrogen was denoted ionometrically by means of ionselective electrode produced by Orion Co. The difference between the content of total nitrogen and concentrations of $N-NO_3^-$ and $N-NH_4^+$ yielded an approximate content of organic nitrogen.

Potassium, calcium and sodium concentration was counted by photometric method (using flame photometer), having formerly burnt a sample of deposit after evaporation and its dissolution in hydrochloric acid. Magnesium was denoted by atomic absorption method in a sample prepared in an alike manner. Concentration of chlorine in water samples was estimated ionometrically by means of ion-selective electrode. Concentration of $S-SO_4^{-2}$ was denoted by colorimetric method with the help of "Specol" photospectrometer.

4. RESULTS

4.1. AN OUTLINE OF MIRE HYDROLOGY

Hydrology of small mires lacking watercourses and located in lakeland hilly landscape, bases on underground water flows. Hydrological conditions of these flows through the studied mires were fairly diversified. Thickness hydrologically active layers in particular mires differed greatly. In the mire with minerotrophic fen (MT) the layer in question comprised the entire peat deposit along with mineral cover, in the mire (MS) – about 60% of peat deposit thickness while in the mire with ombrotrophic-transition bog – only a tiny part of its thickness. The examined mires were surrounded by moderately and locally hardly permeable grounds whose mean hydraulic conductivity index ranged 0.38–1.41 $m \cdot d^{-1}$. Desaturation of these grounds as well as of mineral-organic layers in the mires amounted, on the whole, to 0.10–0.13. However, desaturation of peats in water flow sites varied from 0.13 in the mire (MT) up to 0.34 in the mire (MS). In case of the mire with ombrotrophic-transition bog the examined parameter varied in different periods of time, assuming values 0.07–0.16 (unpublished data). Hence in all the mires under studies there were more or less favourable conditions for water flow, mineral substances included.

The most diversified structural element of water conditions in the studied systems were the factors determining a relative amount of groundwater inflow from catchment area to the mire. The catchment area of the mire with minerotrophic fen (MT) was as much as 20 times greater than the mire itself. In case of the mire (MS) the ratio amounted to 7, whereas the catchment area of the mire with ombrotrophic-transition bog (O-T) was merely twice as large as the mire (Table 3). Hence the mires with minerotrophic fen had much more advantageous conditions for receiving ground water along with the load of mineral elements it carried.

Table 3. Water balances (annual) of the studied mires against their catchment area characteristic

Components of mire hydrology		Mire with minerotrophic fen (MT)				Mire with minerotrophic fen (MS)				Mire with ombrotrophic-transition bog (O–T)			
		June 1982– –May 1983		June 1983– –May 1984		May 1982– –Apr. 1983		May 1983– –Apr. 1984		June 1982– –May 1983		June 1983– –May 1984	
		m^3	mm	m^3	mm	m^3	mm	m^3	mm	m^3	mm	m^3	mm
Input	precipitation	310.1	608	181.3	356	1123.3	614	671.6	367	2868.4	583	1782.5	362
	inflow	1030.8	2021	648.5	1272	1688.4	923	827.5	452	659.3	134	932.3	190
	retention	183.6	360	188.3	369	1892.6	1034	1112.3	608	1436.8	292	1368.0	278
Output	evapotrans-piration	439.5	862	303.8	596	1536.1	839	657.9	360	2899.5*	589*	2891.7*	588*
	outflow	848.2	1663	539.9	1059	1220.9	667	905.3	495	521.0	106	385.0	78
	retention	236.8	464	174.4	342	1947.3	1065	1048.2	572	1544.0	314	806.1	164
The area of mire catchment basin to the mire area		20.1				7.0				2.0			

*Potential evapotranspiration.

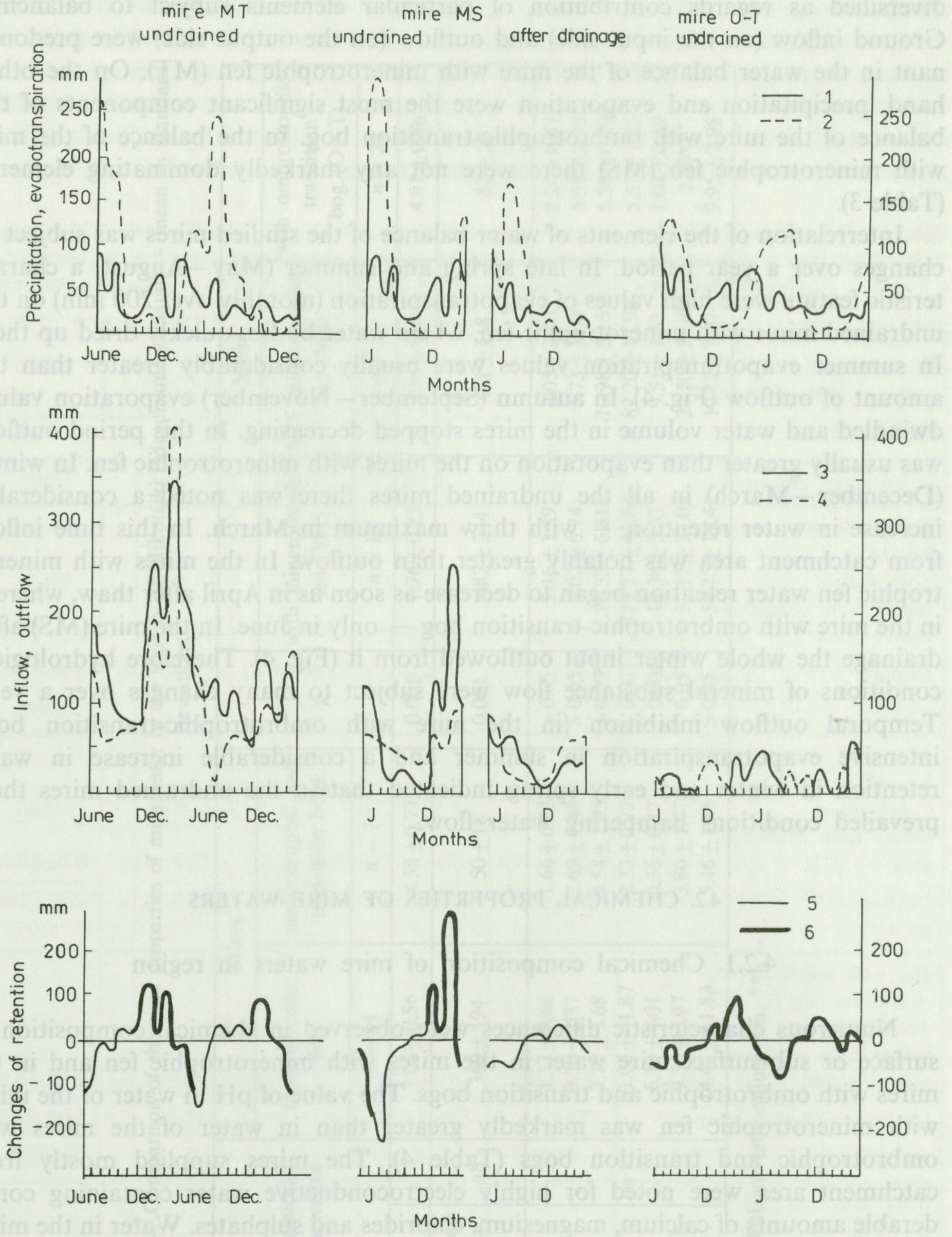

Fig. 4. The course of changes in precipitation, evapotranspiration, inflow, outflow and water retention in the studied mires

1 — precipitation, 2 — evapotranspiration, 3 — inflow, 4 — outflow, 5 — changes in ground retention, 6 — changes in ground and surface retention (occurrence of water bodies on the mire surface)

Consequently, annual water balances in the examined mires were distinctly diversified as regards contribution of particular elements subject to balancing. Ground inflow (on the input side) and outflow (on the output side) were predominant in the water balance of the mire with minerotrophic fen (MT). On the other hand, precipitation and evaporation were the most significant components of the balance of the mire with ombrotrophic-transition bog. In the balance of the mire with minerotrophic fen (MS) there were not any markedly dominating elements (Table 3).

Interrelation of the elements of water balance of the studied mires was subject to changes over a year period. In late spring and summer (May – August) a characteristic feature were high values of evapotranspiration (monthly over 200 mm) on the undrained mires with minerotrophic fen, where water bodies quickly dried up then. In summer evapotranspiration values were usually considerably greater than the amount of outflow (Fig. 4). In autumn (September – November) evaporation values dwindled and water volume in the mires stopped decreasing. In this period outflow was usually greater than evaporation on the mires with minerotrophic fen. In winter (December – March) in all the undrained mires there was noted a considerable increase in water retention – with thaw maximum in March. In this time inflow from catchment area was notably greater than outflow. In the mires with minerotrophic fen water retention began to decrease as soon as in April after thaw, whereas in the mire with ombrotrophic-transition bog – only in June. In the mire (MS) after drainage the whole winter input outflowed from it (Fig. 4). Therefore hydrological conditions of mineral substance flow were subject to many changes over a year. Temporal outflow inhibition (in the mire with ombrotrophic-transition bog), intensive evapotranspiration in summer and a considerable increase in water retention in winter and early spring indicated that in the undrained mires there prevailed conditions hampering water flow.

4.2. CHEMICAL PROPERTIES OF MIRE WATERS

4.2.1. Chemical composition of mire waters in region

Numerous characteristic differences were observed in chemical composition of surface or sub-surface mire water in the mires with minerotrophic fen and in the mires with ombrotrophic and transition bogs. The value of pH in water of the mires with minerotrophic fen was markedly greater than in water of the mires with ombrotrophic and transition bogs (Table 4). The mires supplied mostly from catchment area were noted for highly electroconductive water containing considerable amounts of calcium, magnesium, chlorides and sulphates. Water in the mires with ombrotrophic and transition bogs was comparingly less electroconductive and contained smaller amounts of the ions in question except for Cl^-. Water of the two types of mires did not differ significantly in concentration of nitrogen, potassium and sodium. Differences in chemical properties of water coming from central parts of the three studied mires resulted from various types of mire water supply (Table 4).

Table 4. Comparison of chemical properties of mire water in the vicinity of Mikołajki (Masurian Lakeland) – mean ± standard deviations

Chemical characteristic		Mires		p	Mires		
		minerotrophic fens	ombrotrophic and transition bogs		with minerotrophic fen (MT)	with minerotrophic fen (MS)	with ombrotrophic-transition bog (O–T)
		$n = 11$	$n = 7$		$n = 13$	$n = 5$	$n = 22$
pH		7.06±0.56	4.58±0.77	0.001	7.76±0.23	7.49±054	4.91±0.36
Electro-conductivity	μS	360±194	50±18	0.001	682±244	471±118	82±26
N*	$mg \cdot l^{-1}$	1.32±0.68	1.66±0.73	>0.05	2.16±1.89	2.05±2.46	2.20±0.57
K		3.30±2.37	2.69±1.48	>0.05	7.02±6.74	1.73±1.00	5.51±2.35
Na		7.12±3.68	4.54±1.55	>0.05	16.33±6.81	10.98±5.15	6.58±0.99
Ca		61.05±41.87	2.33±0.72	0.001	139.27±43.84	82.20±12.97	5.37±1.85
Mg		6.10±4.01	0.36±0.17	0.002	13.38±5.53	9.51±1.53	1.04±0.39
$S-SO_4$		9.35±5.97	3.80±1.77	0.05	32.17±27.05	24.50±38.49	2.70**
Cl		14.47±11.83	5.46±1.85	>0.05	54.75±19.41	19.12±7.07	9.95±2.98

*Without ammonium ion. **$n = 1$.

4.2.2. Chemical characteristic of water inflowing and outflowing from the mires

As it has already been mentioned above, water inflowed to the mires from two sources, namely, atmosphere and catchment area. Chemical composition of those two types of water was different. Precipitation water was considerably less electroconductive than groundwater of catchment area (Table 5). Moreover certain elements were marked for similar concentration in water from the two types of

Table 5. Characteristic of element concentration in water inflowing from atmosphere (J. R. Zimka and from mires (mean and standard deviation). Characteristic of element concentration in total inflow significance level ($p \leqslant 0.05$) concerns differences in element concentrations in inflow from

Type of water		Electro-conduc-tivity	$N-NH_4$	$N-NO_3$	N org.	N
		µS				
Inflow from atmosphere		33	1.50	0.74	0.58	2.82
Mire with minerotrophic fen (MT):						
Total inflow		669	1.14	4.61	0.87	6.63
Inflow from catchment area	$n=24$	855±66	1.04±0.82	5.74±4.36	0.96±1.27	7.74±3.96
Outflow	$n=24$	957±147	0.81±0.58	0.39±0.38	1.71±2.36	2.90±2.68
$p \leqslant 0.05$		–	–	0.001	–	0.001
Mire with minerotrophic fen (MS):						
Total inflow		296	1.18	1.11	0.68	2.96
Inflow from catchment area	$n=12$	471±62	0.96±0.77	1.36±0.71	0.74±0.88	3.06±1.64
Outflow	$n=12$	478±66	0.72±0.58	0.04±0.05	0.65±0.14	1.41±0.64
$p \leqslant 0.05$		–	–	0.001	–	0.05
Mire with ombrotrophic-transition bog (O–T):						
Total inflow		222	1.42	1.83		3.25
Inflow from catchment area	$n=14$	773±102	1.19±0.69	3.31±2.86		4.50±2.52
Outflow	$n=10$	354±126	1.46±1.89	1.54±0.80		3.00±1.97
$p \leqslant 0.05$		0.001	–	–		–
Mire with minerotrophic fen (MS) after drainage:						
Total inflow		297	1.03	0.68	0.57	2.29
Inflow from catchment area	$n=12$	511±62	0.65±0.52	0.64±0.60	0.57±0.14	1.86±1.11
Outflow	$n=12$	534±81	0.58±0.48	1.94±2.04	1.25±0.36	3.77±2.24
$p \leqslant 0.05$		–	–	0.05	0.001	0.05

sources (N, K), whereas others had by several or more times smaller concentration in precipitation than in ground water (Na^+, Ca^{2+}, Mg^{2+}, $S-SO_4{}^{2-}$ and Cl^-). In case of nitrogen forms, concentration of ammonium ion was always greater in precipitation water, while nitrate ion occured in markedly greater concentration in water from catchment area (Table 5).

Water inflowing the mires from mineral grounds contained fairly large amounts of elements. Differences between particular mires in this respect seemed to result

A. Stachurski – unpublished), in water inflowing to mires from catchment areas and in water outflowing – weighed means of concentrations in inflows from atmosphere and catchment areas. Statistical catchment area and in outflow. Significantly higher concentrations were underlined

K	Na	Ca	Mg	$S-SO_4$	Cl
	mg·l^{-1}				
0.61	1.27	1.27	0.20	1.44	2.34
0.86	12.89	127.74	12.08	27.58	40.39
0.93±0.48	16.29±1.94	164.75±8.62	15.56±1.80	35.23±4.60	51.52±11.34
4.77±2.62	15.51±3.25	161.75±40.09	16.37±3.80	36.81±24.60	63.40±23.66
0.001	–	–	–	–	–
0.62	6.09	50.79	6.02	6.11	12.33
0.62±0.26	9.30±1.00	83.74±9.06	9.90±1.40	10.05±1.69	18.98±11.56
0.95±0.44	7.81±1.12	86.09±20.83	8.05±1.58	8.04±3.96	20.61±52.55
–	–	–	–	–	
0.96	4.55	38.88	3.28	8.29	18.13
1.98±1.04	14.15±2.94	148.77±34.70	12.29±3.22	28.32±7.72	64.28±15.00
5.39±2.93	8.74±3.51	58.92±23.75	4.62±1.44	1.61±0.67	33.87±22.97
0.001	0.001	0.001	0.001	0.001	0.01
0.74	5.97	50.23	5.91	6.17	12.65
0.84±0.26	9.78±1.24	89.97±11.40	10.55±1.81	10.00±1.27	21.01±5.98
0.52±0.25	9.81±3.78	88.76±22.44	8.93±1.35	33.86±22.49	18.24±6.65
–	–	–	–	0.05	

from various contribution of intensively fertilized ploughland to catchment area. Electroconductivity as well as the content of nitrogen sulphates and chlorides in water inflowing to the mid-field mire (MT) were much greater than in water inflowing the mire (MS), whose catchment area was under crop field-meadow use (Table 5). A comparative analysis between chemical composition of water inflowing and outflowing from the mires may be carried out from two aspects. Concentration of elements in outflow water may be compared to their concentration in inflow ground water, or to the mean (weighed) concentration in total inflow water, i.e. from catchment area and precipitation.

Electroconductivity of inflow and outflow water of the mires with minerotrophic fen was little diversified. On the other hand, in case of the mire with ombrotrophic--transition bog electroconductivity of outflow water was twice as small as of inflow ground water. However the difference disappeared if values of this parameter in inflowing precipitation water were considered (Table 5).

Notable differences between the mire inflow and outflow water were observed with regard to nitrogen concentration. Water flowing out from the undrained mires with minerotrophic fen contained 2.0 – 2.5 times less total nitrogen than inflow water (Table 5). Slightly smaller differences between nitrogen concentrations in the inflow and outflow water were noted in the mire with ombrotrophic-transition bog (especially if the total inflow was analyzed). During drainage of the mire (MS) the examined ratio was inverse, i.e. concentration of total nitrogen was higher in outflow water. The pronounced decrease in nitrogen concentration in water of the undrained mires with minerotrophic fen resulted from a sharp drop in the concentration of nitrate ion in their water. A three times greater concentration of nitrates was noticed in the outflow water from the drained mire (MS). Concentrations of other nitrogen forms were not so pronouncedly contrasted as those of nitrates. Only in case of organic nitrogen its concentration in outflow water of the mires (MT) and (MS) after drainage, was two times greater (Table 5). Fairly diversified were also changes in potassium concentration in mire water. Most striking was an increase in its content in 1 l of outflow water, which in case of the mire with minerotrophic fen (MT) and with ombrotrophic-transition bog (O-T) was manifold. In the mire (MS) concentration of potassium in outflow water did not tend to increase so markedly (Table 5).

Concentration of Na^+, Ca^{2+}, Mg^{2+} and Cl^- in water from catchment area of the mires with minerotrophic fen was, on the whole, approximate. However if precipitation water was considered in the inflow analysis, the situation was different, namely, their concentration were greater in outflow water (Table 5). In the mire with ombrotrophic-transition bog concentration of the ions in question was much greater in water inflowing from catchment area than in water of total inflow (from land and atmosphere) (Table 5), for the mire was primarily supplied with precipitation water, poor in the discussed elements. Consequently, although concentration of these elements was greater in outflow than in total inflow to the mire, yet it was several times smaller than in water from catchment area (Table 5).

Concentration of sulphate sulphur in the undrained mires with minerotrophic fen was much alike in inflow and outflow water. During a year-long drainage of the mire

(MS) there was, however, noted a multiple increase in the concentration of sulphate ion in outflow water. As compared to inflow water, a marked decrease in $S-SO_4^{2-}$ concentration was observed in outflow water in the mire with ombrotrophic-transition bog (Table 5). Statistical variation of the estimated values of element concentrations in the mire inflow and outflow water did not exceed 32% on the average (Table 6).

Table 6. Statistical variance of element concentrations in various sampling stations in inflow and outflow zones of the studied mires Mean variability index (*V*) in 5–8 samples of 2 or 3 elements and its standard deviation (*SD*)

Statistical parameter	N	K	Na	Ca	Mg	$S-SO_4$	Cl
V	32	26	10	13	18	17	17
±*SD*	15	21	7	11	12	13	12

4.3. MAIN FEATURES OF ELEMENT PROCESSING IN MIRES

4.3.1. Element processing in the mires with minerotrophic fen

The studied mires with minerotrophic fen (occupying lower, tiny sections of complex agricultural – swampy catchment area) were marked for prevalence of underground inflow water over precipitation and about 45–65% outflow index (outflow to total inflow ratio) (Tables 7, 8). With respect to hydrology, they ranked among sites of a distinct flow character. Nonetheless, balances of elements transporting through the mires were varied.

In the undrained mires (MT) and (MS), positive balances of total nitrogen were noted: 70–80% of the element inflow was not stated in the outflow from the mires (Table 7, 8). In absolute values, a decrease in nitrogen outflow may exceed $100\ kg \cdot ha^{-1} \cdot year^{-1}$. High positive values of total nitrogen balance were brought about by hardly any outflow of $N-NO_3^-$ (Table 7, 8) and, to a smaller extent, by positive balances of ammonium ion (25–70% of total inflow). Only the water-dissolved organic form of nitrogen followed a more diversified transport pattern. In the mire (MS) its outflow tended to decrease (Table 7), yet in the mire (MT) a distinct adverse or equipoised balance (Table 8) was observed.

Potassium processing by the mires with minerotrophic fen may be fairly diversified. A 4-times greater outflow than inflow of this element in the mire (MT) attests to the fact that the mires with minerotrophic fen may be a temporary source of K^+, markedly enriching water in this element (Table 7). An increased output of potassium by this mire seemed most likely to result from intensive leaching of this element from clayey materials in a periodically flooded layer of slope origin. It was proved by a distinct correlation ($r = 0.86$) between concentration of K^+ in the mire surface water abutting on this layer and the element content in outflow from the mire

Table 7. Balances of elements in dissolved form in the undrained mire with minerotrophic fen (MT) against its hydrology ($kg \cdot ha^{-1} \cdot yr^{-1}$)

Element of balance		Year	$N-NH_4$	$N-NO_3$	$N_{org.}$	N	K	Na	Ca	Mg	$S-SO_4$	Cl	H_2O	
													$\frac{I_c^*}{I_a}$	$\frac{O^{**}}{I_t}$
Inflow (*D*)	from atmosphere	1	9.12	4.50	3.53	17.15	3.71	7.72	7.72	1.22	8.76	14.23		
		2	5.33	2.63	2.06	10.02	2.17	4.51	4.51	0.71	5.12	8.32		
	from catchment	1	31.41	130.20	14.25	175.86	14.53	326.62	3289.09	319.63	702.78	974.97		
		2	6.57	63.95	15.44	85.96	14.56	208.78	2120.68	194.63	453.85	696.84	3.32	0.63
Outflow (*O*)		1	12.92	5.04	34.59	52.55	56.68	224.53	2898.28	287.17	595.91	1098.81	3.58	0.65
		2	8.88	4.98	14.17	28.03	64.97	185.53	1579.79	163.77	400.11	642.85		
Balance (*D* – *O*)		1	27.61	129.66	–16.81	140.46	–38.44	109.81	398.53	33.68	115.63	–109.61		
		2	3.02	61.60	3.33	67.95	48.24	27.76	545.40	31.57	58.86	62.31		
Balance in % of inflow		1	68.1	96.3	–94.5	72.8	–210.7	32.8	12.1	10.5	16.3	–11.1		
		2	25.4	92.5	19.1	70.8	–288.3	13.0	25.7	16.2	12.8	8.8		

$\frac{*I_c}{I_a}$ = Inflow from catchment area: inflow from atmosphere. $\frac{**O}{I_t}$ = Outflow : total inflow.

Table 8. Balances of elements in dissolved form in the undrained mire with minerotrophic fen (MS) against its hydrology ($kg \cdot ha^{-1} \cdot yr^{-1}$)

Element of balance		$N-NH_4$	$N-NO_3$	$N_{org.}$	N	K	Na	Ca	Mg	$S-SO_4$	Cl	H_2O	
												$\frac{I_c{}^*}{I_a}$	$\frac{O^{**}}{I_t}$
Inflow (*D*)	from atmosphere	9.21	4.54	3.56	17.31	3.74	7.80	7.80	1.23	8.84	14.36	1.50	0.43
	from catchment area	8.81	12.54	6.85	28.20	6.01	85.83	772.65	91.34	92.75	175.10		
Outflow (*O*)		4.78	0.26	4.36	9.40	6.32	52.13	574.35	53.69	53.63	137.49		
Balance (*D*−*O*)		13.24	16.82	6.05	36.11	3.43	41.50	206.10	38.88	47.96	51.97		
Balance in % of inflow		73.5	98.5	58.1	79.3	35.2	44.3	26.4	42.0	47.2	27.4		

* and ** – For explanation see Table 7.

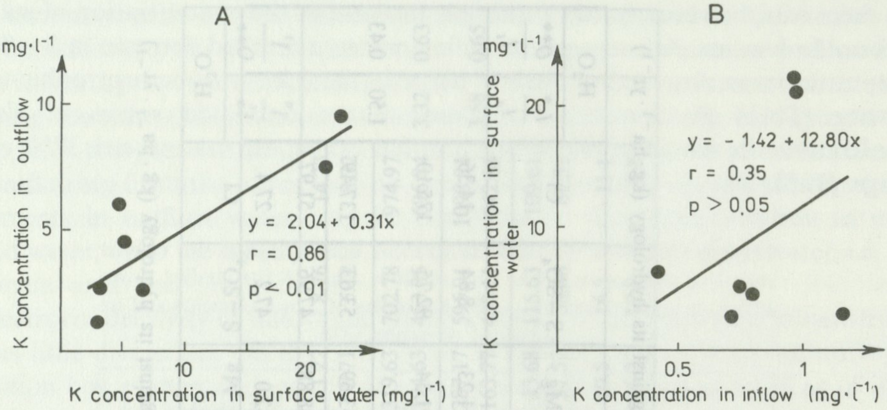

Fig. 5. A – Concentration of potassium in inflow water in the mire with minerotrophic fen (MT) (*y*) as function of its concentration in water of surface basin on the mire (*x*) in the months November–March, B – Dependence between potassium concentration in inflow water to the mire with minerotrophic fen (MT) (*x*) and its concentration in water of surface basin on the mire (*y*) in the months November–March

in time vegetation cover was not active (Fig. 5). Potassium concentration in mire water was not affected in that time by water flowing into the mire from catchment area (Fig. 5). In the mire (MS) a favourable balance of potassium was noted, a tendency being observed for decreasing outflow of this element (Table 8).

In case of the other elements (Na^+, Ca^{2+}, Mg^{2+}, $S-SO_4^{2-}$ and Cl^-), there were not recorded any high relative values of their balances on the mires with minerotrophic fen. In the mire (MT) the recorded balances were most frequently distinctly equiposed, their values ranging from −11 to +16% of the total inflow of the studied elements. Only the balance of sodium in the first and of calcium in the second year of studies indicated a certain set-back in outflow of these elements (Table 8). On the other hand, the results of balance analysis for the mire (MS) pointed to a check in the outflow of the studied elements ranging from 27% of the Cl^- inflow up to 47% of $S-SO_4^{2-}$ input (Table 8). Attention should be paid to considerable amounts of particular elements, retained over a year by the mires with minerotrophic fen, e.g., about 200–550 kg $Ca \cdot ha^{-1}$ about 50–115 kg $S-SO_4^{2-} \cdot ha^{-1}$ and about 30–110 kg $N \cdot ha^{-1}$ (Tables 7, 8).

Small, undrained mires with minerotrophic fen affected by conditions favouring temporal retention of surface water and substantially supplied from catchment area, seem to be most exposed to changeability of hyrdological factors (e.g. varying precipitation, thaws). With this in mind, it was studied whether the pool of plant-available elements (in dissolved form) in the mire was not subject to changes from year to year. The comparison was drawn on the basis of the nutrient pool occurring in the mire in subsequent spring periods (April–May) – before or after an early stage of vegetation upgrowth. It turned out that changes in the element pool could exceed 60%. In most cases the pool of elements was greater in the following year which meant that water in the mires with minerotrophic fen was enriched (Table 9).

Table 9. Annual changes in the pool of elements in dissolved form in undrained mires with minerotrophic fen, recorded in successive spring periods — means from 2 months ($kg \cdot ha^{-1}$)

Mire	Element pool	N	K	Na	Ca	Mg	$S-SO_4$	Cl
MT	p_1	20.44	6.47	54.71	581.17	62.68	61.96	147.00
	p_2	29.32	11.13	58.80	591.43	56.55	69.39	220.08
	p_3	12.42	21.56	62.10	499.37	45.86	78.06	212.77
	change in pool $p_2 - p_1$	−8.88	−4.66	−4.09	−10.26	6.13	−7.43	−73.08
	$\frac{p_2 - p_1}{p_1} \cdot 100\%$	−43.4	−72.0	−7.5	−1.8	9.8	−12.0	−49.7
	change in pool $p_3 - p_2$	16.90	−10.43	−3.30	92.06	10.69	−8.67	7.31
	$\frac{p_3 - p_2}{p_2} \cdot 100\%$	57.6	−93.7	−5.6	15.6	18.9	−12.5	3.3
MS	p_1	25.00	6.38	76.72	765.47	72.80	68.50	136.25
	p_2	24.18	9.14	109.59	1012.83	106.98	126.07	206.14
	change in pool $p_2 - p_1$	0.82	−2.76	−32.87	−247.36	−34.18	−57.57	−69.89
	$\frac{p_2 - p_1}{p_1} \cdot 100\%$	3.3	−43.3	−42.8	−32.3	−47.0	−84.0	−51.3

Distinct enrichment of mire water in nutrients was recorded in the mire (MS). The pool of water-dissolved elements under study (except for nitrogen) increased there by 40–50% (Table 9).

4.3.2. Processing of elements in the mire with ombrotrophic-transition bog

The mire with ombrotrophic-transition bog (O-T) differed from the other mires in a number of hydrological aspects. Firstly, in certain periods of time the mire in question was a receiver of water from its relatively tiny catchment area whereas some other time it acted as a divide for larger catchment area systems. The topographic location causing this form of water conditions resulted in the fact that the inflow of precipitation water to the mire (O-T) was three times greater than the inflow from its catchment area (in case of the mires with minerotrophic fen the ratio was inverse). Moreover, the outflow index, which in case of this mire amounted merely to about 15%, was several times smaller than that estimated for the mires discussed above (Table 10). Hence hydrology of the mire (O-T) was grounded on the exchange with atmosphere.

Positive balance of total nitrogen in the mire with ombrotrophic-transition bog (O-T) amounted up to 84–89%, while of its forms (ammonium and jointly nitrate and dissolved organic form) – to 76–95% of the inflow. However, the amounts of nitrogen which did not flow out from the examined mire were several times smaller than in the mires with minerotrophic fen and did not exceed 20 $kg \cdot ha^{-1} \cdot yr^{-1}$ (Table 10).

The mire with ombrotrophic-transition bog variously processed potassium. In one year potassium balance was positive yet it was adverse in the other (Table 10).

Table 10. Balances of elements in dissolved form in the undrained mire with ombrotrophic-transition bog (O – T) against its hydrology ($kg \cdot ha^{-1} \cdot yr^{-1}$)

Element of balance		Year	$N-NH_4$	$N-NO_3 + N_{org.}$	N	K	Na	Ca	Mg	$S-SO_4$	Cl	H_2O	
												$\frac{I_c^*}{I_a}$	$\frac{O^{**}}{I_t}$
Inflow (*D*)	from atmosphere	1	8.75	7.70	16.45	3.56	7.40	7.40	1.17	8.40	13.64	0.23	0.15
		2	5.43	4.78	10.21	2.21	4.60	4.60	0.72	5.22	8.48		
	from catchment area	1	1.64	5.47	7.11	3.52	17.95	210.85	18.39	35.24	85.64		
		2	2.16	4.86	7.02	2.54	28.24	265.66	20.58	57.50	122.52		
Outflow (*O*)		1	2.52	1.28	3.80	3.63	6.22	46.57	4.02	2.27	20.71	0.52	0.14
		2	0.42	1.47	1.89	5.75	8.99	57.77	4.25	0.85	37.68		
Balance (*D* – *O*)		1	7.87	11.89	19.76	3.45	19.03	171.68	15.54	41.37	78.57		
		2	7.17	8.17	15.34	–1.00	23.85	212.49	17.05	61.87	93.32		
Balance in % of inflow		1	75.7	90.3	83.9	48.7	75.0	78.7	79.4	94.8	79.1		
		2	94.5	84.8	89.0	–21.2	72.6	78.6	80.0	98.6	71.2		

* and ** – For explanation see Table 7.

Balances of Na^+, Ca^{2+}, Mg^{2+} and Cl^- were not subject to changes from year to year and accounted for 70–80% of the inflow of these elements. Almost completely checked (in 95–99%) was the outflow of sulphate sulphur from the mire in question (Table 10). Notwithstanding high values of budget indices, the amounts of retained over the year in the mire with ombrotrophic-transition bog were, on the whole, smaller than in the mires with minerotrophic fen.

Changes in particular nutrient pool in water of the mire (O-T) in subsequent spring periods did not vary greatly, amounting upmost to 30% (Table 11). Furthermore, it was many times smaller than the amounts retained in the mire as shown by the comparison of data from Table 10 and Table 11.

Table 11. Annual changes in the pool of elements in dissolved form in the undrained mire with ombrotrophic-transition bog (O–T), recorded in successive spring periods – means from 2 months ($kg \cdot ha^{-1}$)

Element pool	N	K	Na	Ca	Mg	$S-SO_4$	Cl
p_1	7.44	10.72	16.98	104.31	6.76	7.23	48.10
p_2	5.96	10.32	18.56	88.04	5.82	5.07	56.28
p_3	4.57	7.69	14.83	73.97	4.75	5.89	47.46
Change in pool p_2-p_1	1.48	0.40	−1.58	16.27	0.94	2.16	−8.18
$\frac{p_2-p_1}{p_1} \cdot 100\%$	19.9	3.7	−9.3	15.6	13.6	29.9	−17.0
Change in pool p_3-p_2	1.39	2.63	3.73	14.07	1.07	−0.82	8.82
$\frac{p_3-p_2}{p_2} \cdot 100\%$	23.3	25.5	20.1	16.0	18.4	−16.2	15.7

4.3.3. Effect of drainage on element processing in the mire with minerotrophic fen

Drainage of the mire (MS) radically altered its water budget. Primarily, surface flood disapeared not to occur again and outflow index increased by almost 40% (Table 12). Hence the features attesting to a flowable character of the mire were more pronounced. Element balances were estimated after a vehement of surface water from the mire (i.e. after about 10 days). In the first year following drainage of the mire (MS) total nitrogen balance was equipoised (Table 12). Hence retentability of this element was abruptly changed by drainage, decreasing by about 100% (Table 12). The prime cause was a distinctly adverse of nitrate ion – while its outflow was blocked by the mire before drainage, then after drainage its outflow was excessive.

An artificial increase in water outflow from the mire affected also the budget of dissolved organic form of nitrogen. Its balance was noted to change from positive to intensively adverse (Table 12). However no differences were spotted in the balance of ammonium nitrogen (Table 12). Unlike nitrogen, potassium processing by the drained mire (MS) was altered so that outflow of this element was reduced (Table 12). Retentability of potassium by the mire devoid of surface flood grew by about 60%.

Table 12. Balances of elements in dissolved form in the minerotrophic mire (MS) after drainage against its hydrology

The effect of drainage on relative values of element balances: $\frac{\text{balance after drainage} - \text{balance before drainage}}{\text{balance before drainage}} \cdot 100\%$, and on mire hydrology: $\frac{\text{hydrological index after drainage} - \text{index before drainage}}{\text{index before drainage}} \cdot 100\%$; in $kg \cdot ha^{-1} \cdot yr^{-1}$

Element of balance		$N-NH_4$	$N-NO_3$	$N_{org.}$	N	K	Na	Ca	Mg	$S-SO_4$	Cl	H_2O	
												$\frac{I_c^*}{I_a}$	$\frac{O^{**}}{I_t}$
Inflow (*D*)	from atmosphere	5.51	2.72	2.13	10.36	2.24	4.66	4.66	0.73	5.29	8.59	1.23	0.60
	from catchment area	2.92	2.90	2.56	8.38	3.78	44.23	406.83	47.69	45.22	95.02		
Outflow (*O*)		2.86	9.59	6.20	18.65	2.59	48.54	439.09	44.19	167.57	90.25		
Balance (*D*−*O*) Balance in % of inflow		5.57 66.0	−3.97 −70.9	−1.51 −32.0	0.09 0.4	3.43 57.0	0.35 0.7	−27.60 −6.7	4.23 8.7	−117.06 −231.7	13.36 12.9		
The effect of drainage on relative values of balances and hydrology (%)		−10.2	−172.0	−155.1	−99.5	+61.9	−98.4	−125.4	−79.3	−590.9	−52.9	−21.5	39.5

*and ** – For explanation see Table 7.

Increased flowability of the mire after drainage was emphasized by changes in the balances of sodium, calcium and magnesium. Retentability of these elements dwindled by about 80–125% (Table 12). To a smaller extent, a similar change was observed in the balance of chloride ion (Table 12). A strongly adverse balance of sulphate sulphur estimated under conditions after drainage indicated not only abatement of retentability of this element but also activation of sulphur resources in the mire (Table 12). The pool of water-dissolved nitrogen, potassium and sulphate ion in the drained mire was subject to a considerable decrease after one year of the mire drainage (Table 13).

Table 13. Annual changes in the pool of elements in dissolved form in the minerotrophic mire MS after drainage, recorded in the successive spring periods – means from two months ($kg \cdot ha^{-1}$)

Element pool	N	K	Na	Ca	Mg	$S-SO_4$	Cl
p_1	24.55	5.54	55.92	507.40	59.25	169.28	95.28
p_2	17.42	4.20	59.90	463.97	52.57	113.56	113.99
Change in the pool p_2-p_1	7.13	1.34	−3.98	43.43	6.68	55.72	−18.71
$\frac{p_2-p_1}{p_1}\cdot 100\%$	29.0	24.2	−7.1	8.6	11.3	32.9	−19.6

4.3.4. Seasonal changes in element processing by mires

Due to element cycling, the most interesting feature of mire functioning is the co-occurrence of the cycle of vegetation changes and hydrological cycle. After thaw, approximately since the beginning of spring upgrowth of vegetation, water in the mire gradually subsides up till August or September, i.e. till increase in plant biomass is checked. Thus, in autumn, when swamp vegetation returns its annual production, water level in the mire is the lowest in the year. In winter the mire starts to renew its water resources, the process lasting up till early spring maximum of surface flood (Fig. 4).

In order to understand significance of these changes to element processing in mires an analysis was carried out of element balances in inflowing and outflowing ground water in the studied mires in the following periods: spring–summer (May–August), autumn (September–December) and winter–thaw time (January–April). Balance calculations included the following elements: Na^+, Ca^{2+}, $S-SO_4{}^{2-}$ and Cl^-.

In time of vegetation development (May–August) there were usually recorded positive balances of elements in ground water inflowing and outflowing from the mires (Fig. 6). In autumn (September–December) a tendency was observed for an adverse balance of elements. Adverse balances of elements in autumn were most distinct in the mire with minerotrophic fen (MS) and, to a smaller degree, also in the mire with ombrotrophic-transition bog. In winter (January–April) most noteworthy

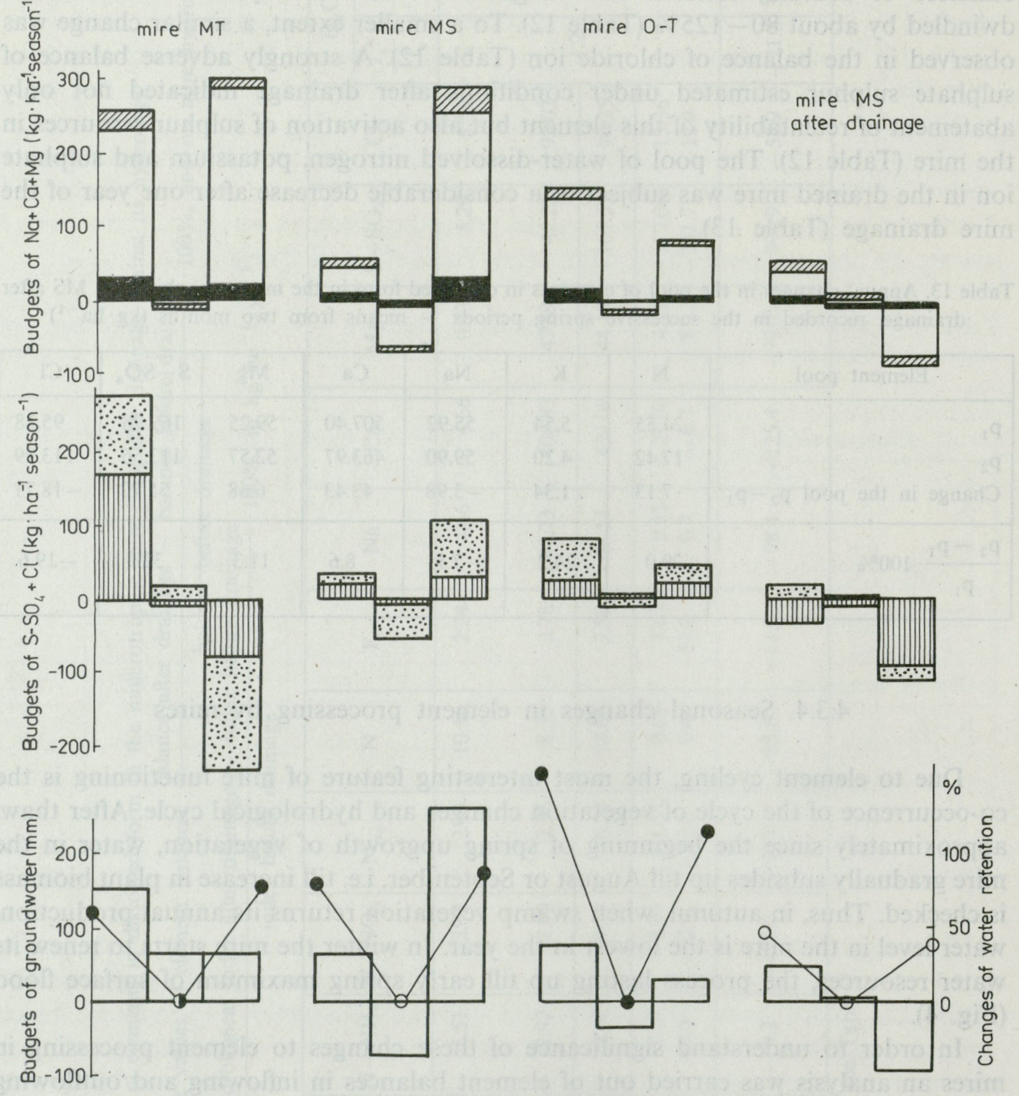

Fig. 6. Seasonal changes in element balances (Na, Ca, Mg, S−SO$_4$, Cl) in subsurface water inflowing and outflowing from the mires against balance of this water and changes in water retention (in % of water volume in hydrologically active layer in the period of low water)

1 — Na, 2 — Ca, 3 — Mg, 4 — S−SO$_4$, 5 — Cl, 6 — ground and surface water retention, 7 — ground water retention

was a profound difference in element processing between undrained mires and the drained one. In case of the former, usually positive balances of elements were estimated, which reflected a tendency to check their outflow. Only in the strongly flowable mire with minerotrophic fen (MT) the examined anions made up adverse balances. On the other hand, in the drained mire (MS) balances of all the examined ions assumed definitely negative values in winter – thaw time. They equalized or even surpassed (in case of Ca^{2+} and $S-SO_4^{2-}$) positive values of balances in full vegetative season (Fig. 6).

Seasonal balances of elements in the mire inflowing and outflowing water seemed to be correlated with balances of this water in particular seasons. In spring – summer time favourable balances of the studied elements corresponded to positive balances (due to intensive evapotranspiration) of water flowing then through the mire (Fig. 6). In autumn a tendency to turn out nutrients was most clearly observed in the mires with adverse balance of underground water. In winter and early spring, positive balances of elements (cations in particular) in the undrained mires were coupled with positive balances of ground water, caused by ineffective ground outflow. However after drainage, balances of both elements as well as drained underground water were adverse (Fig. 6).

Positive balances of water flowing through the mires in winter – thaw time were connected with a considerable augmentation of water retention, up to the occurrence of surface flood. Adverse balance of underground water in the drained mire at that time caused only a slight retention increase, which, however, did not produce flood (Fig. 6). Hence it may be concluded that the mires where large water rise was observed in winter and early spring may be expected to retain nutrients flowing then through them.

4.3.5. Effect of mires on element through-flow in sub-surface water of catchment area

The studied mires betrayed more or less distinct features attesting to their flowable character. Even the mire with ombrotrophic-transition bog, whose water balance was based on the exchange with atmosphere, received and turned out sub-surface water. Water flowing through the examined mires was coming from agricultural areas and having passed the mires it supplied lakes or rivers. Therefore it seemed interesting to examine the effect of mires on elements contained in water flowing through them. Hence a question arose whether mires had any significant effect on the load of nutrients flowing in sub-surface water.

In order to answer the question it was studied if the means of two samples made up of monthly amounts of ground inflows and outflows of the examined elements in particular mires were equal (assuming normal distribution). The asumption of their equality was verified in case of the mires with minerotrophic fen by t-test for difference between two means for pairing correlations samples (inflow and outflow proceeding simultaneously there) and in case of the mire with ombrotrophic-transition bog – by t-test for difference between two means for samples from independent populations (inflow and outflow did not proceed simultaneously there) (Zar 1984).

Table 14. Statistical significance of differences between mean monthly inflows (x_1) and outflows (x_2) of elements in subsurface water flowing through the mires

+ Inflows are statistically significantly greater than outflows; − Inflows are statistically significantly smaller than outflows; When $n_1 = n_2$ t test for difference between two of means for pairing correlations samples was employed; When $n_1 \neq n_2$ t test for difference between two of means for samples from independent populations was employed

Mire	n_1, n_2	$N-NH_4$	$N-NO_3$	$N_{org.}$	N	K	Na	Ca	Mg	$S-SO_4$	Cl
With minerotrophic fen (MT)	n_1, $n_2 = 24$	> 0.05	+ 0.01	− 0.05	+ 0.01	− 0.01	+ 0.01	+ 0.01	> 0.05	> 0.05	> 0.05
With minerotrophic fen (MS)	n_1, $n_2 = 12$	> 0.05	+ 0.05	> 0.05	+ 0.05	> 0.05	> 0.05	> 0.05	> 0.05	+ 0.05	> 0.05
With ombrotrophic-transition bog (O−T)	$n_1 = 14$ $n_2 = 10$	> 0.05	> 0.05		> 0.05	− 0.05	> 0.05	+ 0.05	+ 0.01	+ 0.01	+ 0.05
Minerotrophic (MS) after drainage	n_1, $n_2 = 12$	> 0.05	> 0.05	− 0.01	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05	− 0.05	> 0.05

In the undrained mires with minerotrophic fen the hypothesis of equality of monthly inflows and outflows (at 0.05 significance level) was acceptable only for the flows of ammonium nitrogen, magnesium and chloride ion (Table 14). Monthly inflows of calcium and sodium to the mire (MT) a similar difference was estimated for sulphate sulphur flows (at 0.05 significance level). Furthermore, in the mire (MT) there might occur conditions under which the output of potassium by the mire may significantly (at 0.01 level) exceed its input from catchment area (Table 14). Inflows of total nitrogen and its nitrate form to both mires with minerotrophic fen significantly, though at various levels, surpassed their outflows. On the other hand, flows of dissolved organic nitrogen were diversified – either they brought about no changes or increased its outflow (Table 14).

Exchange of sub-surface water by the mire with ombrotrophic-transition bog (O-T) in the time of studies caused significant reduction in monthly flows of magnesium and sulphate sulphur (at 0.01 level) and of calcium and chloride ion (at 0.05 level). However no significant changes were noted between ground inflows and outflows of nitrogen and its forms as well as sodium. Monthly output of potassium turned out to be significantly greater than its inflows (Table 14).

After drainage of the mire with minerotrophic fen (MS) monthly inflow of any element did not exceed its outflow. At 0.05 significance level, input equaled output of potassium, sodium, calcium, magnesium, chloride ion and total nitrogen (including nitrate and ammonium nitrogen), while outflow of sulphate sulphur and organic nitrogen surpassed their inflow from catchment area (Table 14).

Thus undrained mires may modify through-flow of elements in sub-surface water. Mires with minerotrophic fen have an unmistakably anti-eutrophication effect on nitrogen flows, mires with ombrotrophic-transition bog may, on the other hand, reduce the loads particularly of magnesium and sulphate sulphur.

5. DISCUSSION

Numerous authors stressed the fact that water balance of minerotrophic peatlands was primarily conditioned by water exchange with land, while that of ombrotrophic peatbogs – by water exchange with atmosphere (e.g. Kulczyński 1941/1942, Sjörs 1948, Bay 1967, Gosselink and Turner 1978, Ingram 1983). This regularity applies also to small mires situated in hollows with no surface run-off.

The discussed types of mires notably differed in value of their evapotranspiration. According to Bavina (1972) evaporation from fens may be 1.4 times greater than potential evaporation, while evaporation from raised bogs – upmost 1.1. times greater. Dooge (1975) stated that evaporation from fens exceeded by 5–15% ground evaporation, while from raised bogs – it could even be smaller than the latter. Annual sums of evapotranspiration from ombrotrophic mires assume approximate, usually slightly smaller values than annual sums of precipitation (Ivanov 1953, 1957, Romanov 1961, Baden and Eggelsman 1964, Hemond 1980). These data as well as the fact that evapotranspiration from permanently water-logged ground approximates potential evaporation (Ivanov 1953) allowed, in case of the studied mire with ombrotrophic-transition bog, for assuming the value of potential evapotranspiration estimated on the basis of indirect data. On the other hand, in spring and summer on the examined mires with minerotrophic fen there were noted astonishingly high (over 200 mm · month^{-1}) values of evapotranspiration estimated on the basis of water balance equation. They may have resulted from overlapping of two processes: intensive direct evaporation from shallow and quickly warmed up water bodies found on the mire (Nowak-Drwal et al. 1976) and increased transpiration from reedswamp communities (Otis after Bernatowicz and Wolny 1974, Bernatowicz et al. 1976), especially when macrophytes growing in water bodies (Królikowska 1971).

Annual inflow and outflow of water in the mires corresponded, on the whole, to the course of hydrological cycle. Vehement inflow of water to peatlands in spring was noted by Kulczyński (1941/1942), Ivanov (1957), Bavina (1966), while intensive spring surface outflow was observed by Ivanov (1953) and Bay (1969). The present studies recorded a distinct decrease or even entire lack of outflow from the mire with ombrotrophic-transition bog in summer, which also was observed in sites studied by Bay (1960), Burke (1975a), Eggelsman (1975) and Hemond (1980). A possibility of alternate receiving and return of water from surrounding lands by peatlands located in a water-parting zone was noticed by Kulczyński (1941/1942).

Water cycle significantly affected element balance in the mires. Annual amounts of element input and output depended on mire catchment basin conditions, determining inflow and outflow of water. Ground inflow of elements from catchment area to mires as well as ground outflow from mire watershed were determined by the same hydrological factors, namely, by water flows, which manage waterborne element outflow from catchment areas occupied by forest land ecosystems (Verry 1975, Likens et al. 1977), or from spring watersheds mainly under agricultural use (Warncke 1980). Nonetheless, present balance hydro-chemical analyses turned out a fairly diversified pattern of nutrient processing by mires.

A noteworthy fact was a strong decrease in nitrogen outflow and its nitrate and ammonium form from undrained mires. Similar observations on mires with surface outflow were made by Crisp (1966), Verry and Timmons (1982), Kadlec after Whigham (1982), Hemond (1983), Vitt and Bayley (1984). On the other hand, after mire drainage outflowing water carried considerable amounts of this element. The results of the present work corresponded to data supplied by Nicchols and MacCrimmon (1974), Klopatek (1978) and Ponnamperuma (1982). Lack of any substantial differences in the outflow of nitrogen from a drained and undrained mire was reported by Burke (1975b). In general, however, there occurs a distinct relation between moisture conditions in peatland and a decrease in nitrogen outflow. Thus a question arises what processes condition this phenomenon?

The most likely clue to the answer are microbiological transformation of nitrogen under anaerobic conditions. Under anaerobic conditions in an undrained mire outflow of nitrate nitrogen is minimal, while after mire drainage – under aerobic conditions – it is subject to a pronounced increase, determining equalization of nitrogen balance in mire water. Only in the presence of oxygen there may proceed more intensive mineralization of organic nitrogen and nitrification of ammonium compounds to nitrates (Lityński and Jurkowska 1982). It may not be precluded that certain amount of nitrogen remains in undrained mires in undecomposed organic matter – a slower rate of nitrogen leaching from plant residues under anaerobic conditions was recorded by Davis and Van der Valk (1978). In these conditions nitrogen may be subject to denitrification (Patrick and Tusneem 1972, Barlett et al. 1979) or after further reduction to NH_4^+ it may volatilize to atmosphere in the form of ammonia. The processes in question depend on thermodynamics of subsequent biological transformations and chemical reactions in the cycle of this element (Ryszkowski and Życzyńska-Baloniak after Fotyma et al. 1987). Besides, nitrates along with other nitrogen forms may be absorbed by humic substances in deeper peat layers (Ulehlova 1971, Verhoeven 1983). Sorptive complex of peat soil may also trap certain amounts of ammonium ions (Brinson et al. 1984). Nitrogen mineralization, i.e. its leachability, seems to depend on C:N ratio (Parnas 1975, Envezor 1976, Richardson et al. 1979, Bosatta and Berendsee 1984). Assuming that in undrained mires there may proceed fixation of atmospheric nitrogen as an additional form of its inflow (Gaudet 1978, Buresh et al. 1980, Waughman and Bellamy 1980) it may be considered that decrease in the outflow of this element from the mires was very intensive. Apart from drainage, nitrogen outflow from mires may increase with respect to its inflow, due to its considerable, anthropogenic input (Kadlec after Whigham 1982).

A characteristic trait of potassium transport through the studied mires was a considerable diversification of its balances. Both in the mires with minerotrophic fen and those with ombrotrophic-transition bog, adverse as well as positive balances were recorded. On one hand K^+ is regarded as a very mobile ion in mire systems – in particular it is noted for being rapidly leached from mire vegetation to soil (Ulehlova 1971, Davis and Van der Valk 1978, Sharma and Gopal 1982). On the other hand, its exchangeability in lowmoor peat may not exceed 50% (Richardson et al. 1976), while its resources in peat are several times greater than its content in mire water (Vernhoeven 1986). Burke (1975b) noted a 40% loss in potassium input in an undrained raised bog. Potassium ion was subject to a marked retention in the mire after drainage (Table 12) and most probably after re-flooding of them, mire resources of this element would be leached. A tendency to an increased outflow of K^+ from the mires, observed during present studies seemed to be of periodical character and balance of this nutrient in the studied mires would tend to equipoise over the period of several years.

The obtained results of sodium, calcium and magnesium balances in the mires with minerotrophic fen seem to corroborate the reports of an intensive exchange of these cations by lowmoor peat (Puüstjärvi 1956, Richardson et al. 1976). Mire vegetation retains these elements (mostly in ionized form, i.e. easily leachable — e.g. *Typha latifolia* absorbs considerable amounts of bivalent cations (Ca and Mg) (Czerwiński and Traczyk 1985).

On bogs bivalent cations (calcium and magnesium) are more intensively absorbed by *Sphagnum* mosses and their residues than monovalent cations (sodium and potasium) (Anschutz and Gessner 1954, Bell 1959). High values of retention indices in the studied mire with ombrotrophic-transition bog of calcium, magnesium, sodium and chloride ions might have been related to a notable prevalence of evapotranspiration over outflow, stated during the period of studies.

Processing of sulphate sulphur in the examined mires was diversified. Besides equiposed balances, a tendency to retain this element was also observed. Release and outflow of considerable amounts of sulphur from the mire with minerotrophic fen after drainage would attest, among others, to a likable formation of sulphur resources in mires. Substantial increase in sulphur concentration in surface outflow water after peatland drainage was also noted by Lee et al. (1975). An issue which points to a strong effect of ombrotrophic mires on sulphur cycling in a landscape was the recorded, almost complete blockade of sulphate outflow (Table 10). Most likely this stable, oxygen-free habitat advanced reduction of sulphates.

With respect to the type of processing in the undrained mires, the examined nutrients may broadly be divided into three groups:

1. Nitrogen. The nutrient whose flow through the undrained mires was consistently and notably diminished.

2. Potassium. Unlike nitrogen, there was not observed any distinct (exceeding 50% of inflow) decrease in its outflow from undrained mires. On the contrary, very frequent were adverse balances of this nutrient.

3. The other nutrients: sodium, calcium, magnesium, sulphate and chloride ions. Distribution of values of their relative balances in the studied undrained mires revealed a certain tendency. In the most flowable mire (MT), their balances were almost equipoised, while in the mire with ombrotrophic-transition bog high values of their relative balances were stated. Contrary to nitrogen and potassium, they may be regarded in terms of their "inertia" with respect to hydrological factor. A hypothetical dependence pattern is as follows: a greater flowability and greater dependence on ground inflow from catchment area do not advance retention of the elements in question, whereas the lack of effective flowability and greater indepence from catchment area cause that distinctly positive balances of these nutrient are possible.

On the basis of results of the present studies there was perceived the following pattern of changes in trophic conditions of mire ecosystems occurring in hollows with no surface run-off. The lack of effective outflow in spring (maximum surface flood) coupled with simultaneous vehement inflow of elements from catchment area in thaw water cause that vegetation developing at that time benefits from substantial pool of nutrients. When in autumn these elements are subsequently leached from plants (which in case of fen vegetation proceeds at a high rate, as stated by Boyd (1970), Planter (1970), Ulehlova (1971), Davis and Van der

Valk (1978), a partial flooding impedes the process, while a gradual increase in water retention in winter hampers any greater outflow of elements beyond the mire. Adding the load inflowing with thaw water from catchment area in the beginning of subsequent spring period, there may be recorded enrichment of mire water in nutrients – by the part of nutrient pool from the former cycle of vegetation development, retained in the mire due to the lack of effective outflow. This occurrence was not noted in the drained mire, which had favourable conditions for rapid outflow (Tables 9, 11, 13).

The pattern provides for a possible, constant increase in element retention in the mire over the period of several years. It may result in an increase in vegetation biomass and assimilation of nutrients by plants, which, in turn, may lead to an increase in the amount of matter excluded from cycling and enrichment in nutrients of peat soil.

The process of enrichment in nutrients of peat habitats presented above may explain the observed, e.g. at Masurian Lakeland, expansion of highly productive willow and reed communities capable of retaining considerable loads of elements (Olkowski 1972, Polakowski 1976, Wilpiszewska 1990). This mechanism may also bring about an excessive eutrophication of mires (Peverly 1982, Verhoeven et al. 1983). A contribution to growing over-fertility of mires was most likely deforesting of their catchment areas and, consequently, disturbance of hydrological and geodynamical balance of slopes – in numerous minerotrophic mires occurring amidst ploughlands (including the studied ones) there occur mineral deposits of slope origin. An unquestionable stimulus for advancing processes of eutrophication is an extensive inflow to mires of elements coming from fertilizers. Most likely fairly significant is also dry precipitation of particles blown in due to wind erosion and fertilization (Goszczyńska 1985).

It should be assumed that a mechanism of retaining elements in mires may be distorted by hydrological changes connected with seasonal climatic changes. One of such factors could be, e.g. the lack of surface flood in some years poor in precipitation, or an increase in outflow in years when atmospheric conditions do not favour intensive evapotranspiration. An implicit hint for this assumption is the fact that drainage stifles mire capabilities to retain most macroelements (except for potassium). It should be remembered, however, that the drained mire was examined directly, i.e. the next year, after drainage and therefore it is difficult to predict changes in nutrient processing by the mire in future.

Undrained mires function as very effective "filters" for nitrogen outflow from catchment areas under agricultural use. It is a well-known fact that considerable amounts of this element may penetrate from ploughlands into ground water, especially in nitrate form (e.g. Lityński and Jurkowska 1982). Hence preservation of mires in lakeland catchment areas would be of great significance for impeding processes of eutrophication of lakes and rivers. Other elements may be retained in mires and temporarily, at least, exclided from cycling in catchment area.

It seems that peatlands located amidst crop fields may well contribute to a better "closure" of element cycling in agricultural landscape since, as compared to other land ecosystems, agroecosystems are marked for a considerable "openess" of this cycle (Rodin and Bazilevič 1965, Ryszkowski 1975).

The results of the present studies prove that the occurrence in agricultural lakeland landscape of various types of catchment areas with minerotrophic, transition and ombrotrophic peatlands lacking water courses, is of significance for the receivers of sub-surface water, i.e. lakes and rivers, since it is the areas with no surface run-off that determine constant underground water supply of these water bodies (Drwal 1982).

Preservation of peatlands located in hollows and prevention them from drainage would contribute to maintaining biogeochemical stability of the catchment area-lake (river) system as well as to improvement of regenerating capabilities of agricultural lakeland landscape (Ryszkowski 1979). The present work points to a need for further studies on element processing by mires and their links with adjacent ecosystems.

6. CONCLUSIONS

Small mires located in hollows with no surface outflow notably differed in their hydrological conditions for element flow-outflow index for mires minerotrophic fen was high (45–65%) and low (15%) for mire with ombrotrophic-transition bog.

Mires affected the content of elements in water flowing through them. Concentration of nitrogen in water outflowing from undrained mires were distinctly smaller than in inflowing water, whereas concentrations of main cations and anions – greater (except for the concentration of sulphate sulphur in the mire with ombrotrophic-transition bog).

Undrained mires with minerotrophic fen, intensively supplied in nutrients from catchment area, were noted for strongly limiting outflow, positive balances of nitrogen, nitrate nitrogen in particular (over 100 kg $N \cdot ha^{-1} \cdot yr^{-1}$) and more equipoised (mostly positive) balances of major cations and anions.

Undrained mire with ombrotrophic-transition bog, to which the inflow of elements from catchment area was poor, effectively decreased outflow of sulphate sulphur in particular and other elements as well. However the amounts of particular nutrients retained there were slight – usually markedly smaller than in mires with minerotrophic fen.

In the first year after drainage the mire with minerotrophic fen was observed to reduce its tendency to delimit nitrogen outflow, while its retentability of potassium increased.

In undrained mires located in hollows with no surface run-off quite possible were considerable (up to about 50%) changes in the pool of nutrients occurring in dissolved form, recorded during a year.

In undrained mires, besides retention of nutrients in vegetative season there also occurred nutrient retention in winter and thaw time due to the lack of conditions for effective outflow.

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7. SUMMARY

The studies on element cycling in small peatlands located in agricultural areas were conducted on three model mires, typical of lakeland landscape, displaying diversified ecological features (the study site comparised an agricultural fragment of Masurian Lakeland – Fig. 1, Table 1). Two of the sites were the mires with minerotrophic fen grown with plant communities characteristic of fens (lowmoor peatlands) – one with Typhetum latifoliae and the other with Salicetum pentandro-cinereae (Fig. 2). They were situated in the Jorka river watershed and had vast, with respect to their size, catchment areas (Table 2). After the first year of studies one of the mires was drained. The third peatland assigned for the studies was a mire with ombrotrophic-transition bog, grown mainly with *Sphagnum* cover with *Oxycoccus quadripetalus*, *Vaccinium uliginosum* and *Carex lasiocarpa* in the central part (Fig. 2). The mire was situated on water-parting zone and had a relatively small catchment area (Table 2).

In order to outline element processing by mires the use was made of input-output balance method based on measurements of groundwater flows. Balances of the following elements were estimated: N (including $N-NO_3$, $N-NH_4$ and $N_{org.}$), K, Na, Ca, Mg, $S-SO_4$ and Cl. Input included ground inflow from catchment area and precipitation, while output – ground outflow from undrained mires or outflow by drain pipe from the drained mire. In order to obtain the values of balances of the studied elements expressed in terms of $kg \cdot ha^{-1} \cdot yr^{-1}$, it was necessary to estimate water balances of the mires. They called for employment of numerous hydrogeological methods owing to which flows of shallow underground water were estimated (Fig. 3).

It was observed that conditions of water flow through mires were subject to changes over a year (Fig. 4) – in the undrained mires there prevailed factors hampering water flow. Water balances of the mires with minerotrophic fen were marked for a considerable contribution of ground inflow to the input and outflow to the output, while precipitation and evapotranspiration were more significant in water balance of the mire with ombrotrophic-transition bog (Table 3).

There were examined chemical properties of mire waters on the studied sites (Table 4) and analyses were made of changes in the content of elements in water flowing through the mires (Table 5, 6). The undrained mires with minerotrophic fen were intensively supplied in elements from their catchment areas. Nutrient processing in these mires was noted mainly for a significant decrease in nitrogen outflow (over 100 $kg \cdot ha^{-1} \cdot yr^{-1}$), and particularly of its nitrate form, and, to a smaller extent, also of its ammonium form (Table 7, 8). The mires in question were also noted for their tendency to reduce (up to about 50%) the outflow of sulphate sulphur, magnesium and sodium. Potassium balance was fairly diversified – positive or strongly adverse (there was recorded potassium leaching from deposits – Fig. 5). Balance of calcium and chloride ion seemed to be most equipoised in the discussed type of mires (Table 7, 8).

The undrained mire with ombrotrophic-transition bog was marked for a much poorer inflow of elements. Strongly positive balances of all the examined elements were recorded in this mire, except for potassium, processing of which was unstable. A noteworthy fact was blockade (in 95–99%) of outflow of sulphate sulphur (Table 10).

After drainage, the mire with minerotrophic fen was observed to alter nitrogen processing and nitrate ion in particular – the mire was no longer capable to reduce their outflow. Moreover, balances of sodium and magnesium were more equipoised then. A strongly adverse balance of sulphate sulphur was noted. Distinctly positive balances were estimated solely for potassium and ammonium nitrogen (Table 12).

The pool of elements dissolved in water of the studied undrained mires increased in a year period (Tables 9, 11), yet decreased in water of the drained mire (Table 13). Yearly changes were examined in element flow through the mires. In spring–summer time all the mires retained the loads of elements inflowing from catchment areas while in autumn the elements were turned out (which, however, in case of

the undrained mires did not counterbalance nutrient retention). Winter – thaw time marked the period of element retention by the undrained mires due to an increased water retention, while in the drained mire elements were outflowed then (Fig. 6).

It was ascertained that the mires with minerotrophic fen had an undoubtedly anti-eutrophication effect with respect to nitrogen flows. An alike effect was stated in case of the mire with ombrotrophic-transition bog with respect to sulphate sulphur and magnesium flows (Table 14). Discussion focused on the comparison of the obtained results to data supplied in literature.

8. POLISH SUMMARY

Do badań nad obiegiem pierwiastków w niewielkich torfowiskach położonych na terenach rolniczych wybrano trzy modelowe, typowe dla krajobrazu pojeziernego bagna o zróżnicowanej charakterystyce przyrodniczej (teren badań to rolniczy fragment Pojezierza Mazurskiego – rys. 1, tab. 1). Dwa z nich to torfowiska minerotroficzne ze zbiorowiskami roślinnymi charakterystycznymi dla torfowisk niskich – jedno z szuwarem Typhetum latifoliae, a drugie z wierzbowiskiem Salicetum pentandro-cinereae (rys. 2). Są one położone w systemie zlewniowym rzeki Jorki i posiadają obszerne, w stosunku do swoich powierzchni, zlewnie (tab. 2). Jedno z nich po pierwszym roku badań zostało zdrenowane. Trzecim torfowiskiem wybranym do badań było torfowisko z mszarem ombrotroficznym i przejściowym składające się głównie z kobierca torfowców z *Oxycoccus quadripetalus*, *Vaccinium uliginosum* i *Carex lasiocarpa* w części centralnej (rys. 2). Torfowisko to położone jest na obszarze wododziałowym i charakteryzuje się stosunkowo niewielką zlewnią (tab. 2).

W celu scharakteryzowania gospodarki mineralnej torfowisk użyto metody bilansu typu wejście – wyjście opartej na badaniu przepływów gruntowych. Zbadano bilanse następujących pierwiastków: N (w tym $N-NO_3$, $N-NH_4$ i $N_{org.}$), K, Na, Ca, Mg, $S-SO_4$ i Cl. Wejście obejmowało dopływy: gruntowy ze zlewni i z atmosfery, a wyjście – odpływ gruntowy z torfowisk nie zdrenowanych lub odpływ drenem i odpływ gruntowy z torfowiska zdrenowanego. Aby uzyskać wartości bilansów badanych składników w $kg \cdot ha^{-1} \cdot r.^{-1}$, niezbędne było zestawienie bilansów wodnych torfowisk. W tym celu wykorzystano szereg metod hydrogeologicznych niezbędnych do rozpoznania przepływów płytkich wód podziemnych (rys. 3).

Odnotowano, że warunki przepływu wody przez torfowiska ulegają w ciągu roku zmianom (rys. 4). W bagnach nie zdrenowanych przeważają czynniki utrudniające przepływ wody. Bilanse wodne torfowisk minerotroficznych odznaczają się znacznym udziałem dopływu gruntowego po stronie wejścia i odpływu po stronie wyjścia, natomiast w bilansie torfowiska ombrotroficznego większą rolę odgrywają opad i parowanie (tab. 3).

Scharakteryzowano właściwości chemiczne wód bagiennych na terenie badań (tab. 4) i zbadano jak zmieniają się zawartości pierwiastków w wodach przepływających przez torfowiska (tab. 5, 6). Nie zdrenowane torfowiska minerotroficzne są intensywnie zasilane w pierwiastki ze swoich zlewni. Ich gospodarka mineralna charakteryzuje się przede wszystkim silnym zmniejszaniem odpływu azotu (ponad 100 $kg \cdot ha^{-1} \cdot r.^{-1}$), zwłaszcza jego formy azotanowej, a w mniejszym stopniu amonowej (tab. 7, 8).

Bagna te mogą przejawiać także tendencję do zmniejszania (do ok. 50%) odpływu siarki siarczanowej, magnezu i sodu. Bilans potasu może być natomiast zróżnicowany – dodatni i silnie ujemny (stwierdzono intensywne wymywanie K z osadu – rys. 5). Gospodarka wapniem i jonem chlorkowym wydaje się być w omawianym typie bagien najbardziej zrównoważona (tab. 7, 8).

Nie zdrenowane torfowisko ombrotroficzne i przejściowe odznacza się o wiele uboższym dopływem makroelementów. Odnotowano tutaj silnie dodatnie bilanse wszystkich badanych pierwiastków z wyjątkiem potasu, którego gospodarkę charakteryzuje brak stabilności. Zwraca uwagę blokada (w 95 – 99%) odpływu siarki siarczanowej (tab. 10).

Po zdrenowaniu torfowiska minerotroficznego zmianom ulega zwłaszcza gospodarka azotem, szczególnie jonem azotanowym – torfowisko traci zdolnosć do zmniejszania ich odpływu. Ponadto bilanse sodu i magnezu są teraz bardziej zrównoważone. Odnotowano ponadto silny ujemny bilans siarki siarczanowej. Natomiast wyraźnie dodatnimi bilansami charakteryzują się jedynie potas i azot amonowy (tab. 12).

Pule pierwiastków w formie rozpuszczonej w wodach badanych torfowisk nie zdrenowanych wzrosły w ciągu roku (tab. 9, 11), a w wodach torfowiska zdrenowanego zmalały (tab. 13). Prześledzono zmiany przepływu pierwiastków przez torfowiska w cyklu rocznym. W okresie wiosenno-letnim wszystkie torfowiska zatrzymują dopływające do nich ze zlewni ładunki makroelementów, natomiast na jesieni zaznacza się ich oddawanie (nie równoważące jednak na torfowiskach nie zdrenowanych poprzedniego pochłaniania). Sezon zimowo-roztopowy to na torfowiskach nie odwodnionych okres zatrzymywania pierwiastków w wyniku wzrostu retencji wodnej, a na torfowisku zdrenowanym – ich oddawania (rys. 6).

Stwierdzono, że torfowiska minerotroficzne oddziałują w wysokim stopniu pewności przeciweutrofizacyjnie w stosunku do przepływów azotu. Torfowisko ombrotroficzne i przejściowe oddziałuje w ten sposób na przepływy siarki siarczanowej i magnezu (tab. 14). W dyskusji ustosunkowano się do wyników bilansowych badanych pierwiastków porównując je z danymi z literatury.

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