

JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535



Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences - National Research Institute (ITP - PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT DOI: 10.24425/jwld.2021.139030 2021, No. 51 (X–XII): 188–198

Phosphate and ammonia concentrations in waters from a meadow complex located on peat soils in various range of groundwater level

Andrzej Sapek¹⁾, Stefan Pietrzak²⁾ (b), Dominika Juszkowska²⁾ 🖂 (b), Marek Urbaniak²⁾ (b)

¹⁾ Retired researcher

²⁾ Institute of Technology and Life Sciences – National Research Institute, 3 Hrabska Avenue, 05-090, Falenty, Poland

RECEIVED 25.10.2021

REVIEWED 01.12.2021

ACCEPTED 10.12.2021

Abstract: The aim of the study was to assess the P-PO₄ and N-NH₄ pollution of water in grasslands located on peat soils and to identify the impact of groundwater level on this pollution formation. The research was conducted in 2000–2010 on grounds of ITP-PIB in Biebrza village (Poland). Within lowland fen a total of 18 monitoring points of groundwater and watercourses were established in 6 separate test stands. The subject of the research was water collected from drainage ditches/channels and groundwater, which was taken from wells installed in organic-soil layer and wells whose bottom was 15–20 cm below this layer. Water samples were collected several times a year, and in the case of groundwater, its level was also measured. It was found that: 1) due to concentration level of P-PO₄ and N-NH₄, about 46 and 39% of water samples from organic-soil layer and more than 40 and 37% of water samples from mineral-organic-soil layer respectively, were characterized by poor chemical status; 2) due to the exceeding of the limit values of P-PO₄ and N-NH₄ concentration, water samples from watercourses in over 30 and 27% respectively were not within 1st and 2nd class of surface water quality; 3) P-PO₄ and N-NH₄ concentrations in each water type were statistically significant factor differentiating the average P-PO₄ concentration in groundwater level changing every 10 cm was a statistically significant factor differentiating the average P-PO₄ concentration in groundwater associated with mineral-organic layer of peat soil and average N-NH₄ concentration in each type of water.

Keywords: grassland, groundwater level, peat soils, inorganic nitrogen and phosphorus concentration, soil phosphorus cycle

INTRODUCTION

Contrary to mineral soils, phosphate-phosphorus (P-PO₄) leaching from organic soils is high and generally exceeds 1 kg P·ha⁻¹·y⁻¹ [KOLENBRANDER 1972; RIDDLE *et al.* 2018], particularly from lowland fen peat soils [RUPP *et al.* 2004; STEENVOORDEN 1976]. Drainage and intensive agricultural use of these soils result in oxidation of peat material, thinning the organic horizon and decrease of water-table depth. In order to restore degraded peatlands and reduce their negative environmental effects, various of remedial measures and actions are being undertaken. Proposed restoration measures relate mostly to the elevation of groundwater level in dewatered peat soils. However, increased depth to the water-table promotes mobilisation of P-PO₄ and its leaching into the groundwater [LITAOR *et al.* 2003; MARTIN *et al.* 1997; MEISSNER *et al.* 2003; RENGER *et al.* 2002; ROBINSON *et al.* 1998]. Therefore, rewetting and restoration of Histosols may result in significant phosphorus losses to adjoining aquatic ecosystems, and as a consequence, accelerated eutrophication and deterioration of water quality [LUCASSEN *et al.* 2005; RUPP *et al.* 2004; VENTERINK *et al.* 2002; ZAK *et al.* 2004].

In order to strengthen the scientific foundation in the field of sustainable management of peat soils, the PROWATER project – Program for the prevention of diffuse pollution from degraded and rewetted peat soils [MEISSNER, LEINWEBER 2004] was initiated. As a part of it, Institute of Technology and Life Sciences – National Research Institute (ITP-PIB) in Falenty undertook wide-ranging studies on water pollution by phosphorus (P) and nitrogen (N) in the area of agricultural peat soils. The studies were situated on drained peatland of Kuwasy, which is a part of vast wetlands area in the central Biebrza River basin (northeast Poland). As a result of artificially draining for agricultural purposes about 6,000 ha of peatlands in the 1930s and 1960s, peat-moorsh soils were formed [JASZCZYŃSKI 2015]. Such soils, apart from containing large amount of organic P and N, are also characterized by their laminar structure resulting in variable sorption properties of peat deposits of different origin and strength of P binding [SAPEK 2012]. Considering different factors including soil moisture conditions or precipitation, organic P accumulated in soil could be released to different extent and transformed into forms which undergo leaching [SAPEK 2010; 2014]. Similarly, the moisture conditions of peat soils affect the organic N transformation and can lead to increasing the concentration of dissolved organic nitrogen (DON) and ammonium nitrogen (N-NH₄) in soil water [LAINE et al. 2013]. Previous research on N and P behaviour in peat-muck soils, especially in terms of migration to waters, is rather scarce and does not exhaust cognitive scope of this subject.

The aim of the study was to assess the $P-PO_4$ and $N-NH_4$ pollution of water in grasslands located on peat soils and to identify the impact of groundwater level depth on this pollution formation.

MATERIALS AND METHODS

The research was conducted between 2000 and 2010 on Kuwasy peat bog (53°39' N, 22°34'–22°37' E) located in the Biebrza River basin on grounds of Experimental Station of ITP-PIB in the Biebrza village (northeast Poland). The study site was situated on organic soils formed from sedge (Cariceti) and alder peat (Alneti) with 80–200 cm depth of peat layer. Mineralization process involves soil layers to about 25 cm of depth. The investigations started within the PROWATER project from May 2000 to December 2003 and continued to September 2010 as an Institute's statutory activity. The study area was ditch and channel drained in the 1930s and 1960s and currently is used as an agricultural area (grassland) with groundwater irrigation system, whereby the groundwater level is maintained at 40–60 cm during the vegetation season.

Six separate control and measurement stations were established within study area with a total of 18 monitoring points for ground and surface water (Tab. 1, Fig. 1), which were distant from each other from 0.6 to 5.9 km in a straight line. Distance of these points from surface water sampling points ranged from 60 to 200 m. The groundwater monitoring points were two types of wells with bottom made of PVC pipes (Ø 50 mm). The first type - "S" wells were used to take water samples from organic layer of soil and the second type of wells, with symbol "P", were used to take water samples from mineralorganic soil layer. These wells were perforated along the entire section located in organic soil layer and along the 15-20 cm long section located in mineral soil layer (approx. 20 cm below the organic formation), respectively [JASZCZYŃSKI 2010]. The surface water monitoring points "C" were located in drainage ditches and channels near groundwater monitoring points. Water samples for laboratory analyses were collected once a month, except for the winter period. In some years, there were cases of collecting unusual number of samples per year (from 5 to 16), mainly due to commencement and completion dates of research work and additional analytical needs. "S" and "P" wells were purged by a bailer and a pump to remove accumulated stagnant well water before sample collection. At the same time the groundwater level was measured. In collected water samples the concentration of N-NH₄ and P-PO₄ was determined in the laboratory using automated colorimetric Skalar analyser.

Table 1. Location of monitoring points (MP)

Test stand code	Form of land use	Soil type	Depth of peat layer (cm)	Monitor- ing point code	Location of MP ¹⁾
		MtII de-		K2S	53°39'40.7" N
К2	mown	veloped	0-210	K2P	22°37'14.0" E
	meadow	from alder peat		K2C	53°39'44.2" N 22°37'14.6" E
		MtII de-		K4S	53°39'17.8" N
K4	hay	veloped	0-210	K4P	22°34'25.3" E
	meadow from all peat			K4C	53°39'22.7" N 22°34'32.6" E
		MtII de-	0–78	K5S	53°38'33.1" N
K5	perma- nent	veloped		K5P	22°34'22.9" E
10	pasture	from sedge peat		K5C	53°38'33.4" N 22°34'17.2" E
		MtII de-		K7S	53°38'1.2" N
К7	perma- nent	veloped	0-145	K7P	22°35'4.8" E
	pasture	from sedge peat		K7C	53°38'4.3" N 22°35'9.57" E
		MtII de-		K8S	53°37'46.8" N
К8	tempor- arv	veloped	0-150	K8P	22°35'31.9" E
	meadow	trom sedge peat		K8C	53°37'48.4" N 22°35'21.8" E
	alternate	MtIII de-		K9S	53°36'54.3" N
К9	mown-	veloped	0-135	K9P	22°34'38.7" E
	grazed grassland	trom sedge peat		K9C	53°36'53.6" N 22°34'41.8" E

¹⁾ After: Jaszczyński [2010].

Explanations: MtII = second mucking degree of peat-muck soil; MtIII = third mucking degree of peat-muck soil. Source: own elaboration.

Soil samples were taken from the 5–30 cm layer and then submitted to the laboratory for analysis. Soil pH was measured potentiometrically in 1 M KCl solution. Determination of soil organic matter (SOM) content was made using "loss-on-ignition" method (soil samples burning at 550°C), while total P, calcium (Ca), iron (Fe) content was measured after mineralization of soil samples in a mixture of HNO₃ and HClO₄ according to the method of chemical analyses of organic soils [SAPEK, SAPEK 1997]. N content in soils was determined by the modified Kjeldahl method.

In addition, as a part of research work, meteorological data was also collected. Precipitation sum and air temperature data



Fig. 1. Study site on bog Kuwasy; source: own elaboration

was measured by Biebrza meteorological station (53°39' N, 20°34' E) located near the research area.

For a better understanding of processes taking place in the analysed soil-water systems, the results obtained of ground- and surface water quality were analysed statistically using the Statistica 6 Program. In this regard: a) descriptive statistical analysis of water test results were performed, calculating arithmetic means, medians, standard deviations and minimum and maximum values, b) on the basis of Pearson's and Spearman's correlation coefficients relationships between various analysed factors were assessed, c) statistically significant difference between P-PO₄ and N-NH₄ mean concentration in water and selected intervals of water levels in organic soil layer was determined using the Kruskal–Wallis test (p < 0.05 values were considered as statistically significant).

RESULTS AND DISCUSSION

In the study area peat soils were relatively poor in ash, but richer in P and Ca. There was no significant difference between subsequent monitoring points of soil (Tab. 2). Annual precipitation and mean annual air temperature between 2000 and 2010 ranged between 477 and 793 mm per year and 6.5–8.3°C, respectively (Fig. 2). The highest average rainfall and air temperature for this period occurred in July and August (Fig. 3).

 Table 2. Chemical composition of soil samples from 5–30 cm soil layer

Test		Ignition	Р	N	Ca	Fe			
stand code	рН	losses (%)	g·kg ⁻¹						
K2	5.2	85	1.32	3.54	6.7	2.0			
K4	5.5	78	2.65	3.11	21.0	22.7			
K5	4.6	76	1.70	3.24	13.6	83.2			
K7	5.1	81	1.87	3.42	14.6	45.8			
K8	5.2	82	1.61	3.37	17.5	44.4			
К9	4.7	85	1.21	3.45	16.3	30.2			
Mean	5.1	81	1.55	3.34	14.7	30.6			

Source: own study.

During the entire period between 2000 and 2010 monthly average of groundwater level in organic soil and mineral-organic soil layer ranged from 37.4 to 57.5 cm and from 33.8 to 58.1 cm, respectively (Fig. 4). These measured water-table levels were closely correlated (Pearson's r = 0.834; a = 0.05; n = 508). The average P-PO₄ concentration in water oscillated between 0.76 and 2.01 mg P-PO₄·dm⁻³ in case of water collected from organic soil



Fig. 2. Annual sums of precipitation and mean annual air temperature for the Biebrza meteorological station; source: own study



Fig. 3. Average monthly sums of precipitation and air temperature for the Biebrza meteorological station in years 2000–2010; source: own study



Fig. 4. Average monthly levels of groundwater in "S" and "P" wells; source: own study

layer and between 0.37–4.37 mg P-PO₄·dm⁻³ in case of water from mineral-organic soil layer (Tab. 3) while average N-NH₄ concentration in water from these layers reached values from 4.28 to 12.17 mg N-NH₄·dm⁻³ and from 1.69 to 21.68 mg N-NH₄·dm⁻³, respectively. Large amounts of rainfall in July and August did not have a relatively strong influence on the rise of water-table level because air temperatures in those months were the highest and therefore intense evapotranspiration took place.

The concentrations of N-NH₄ and P-PO₄ were often unusually high as compared with the literature data. Mean concentration of P-PO₄ was 1.23 mg P-PO₄·dm⁻³ in 669 samples of groundwater from organic soil layer and 1.83 mg P-PO₄·dm⁻³ in 508 samples from mineral-organic soil layer (Tab. 3).

Table 3. Ammonium nitrogen $(N-NH_4)$ and phosphate-phosphorus $(P-PO_4)$ concentrations in groundwater and surface water

Descriptive	Grour from o soil	idwater organic layer	Grour from r organ la	ndwater nineral- nic soil yer	Surface water					
statistics	P-PO ₄	N-NH ₄	4 P-PO ₄ N-NH ₄		P-PO ₄	N-NH ₄				
	mg·dm ⁻³									
n	6	69	5	08	671					
Mean	1.23	7.98	1.83	9.69	0.13	0.47				
Median	0.26	0.97	0.17	0.74	0.06	0.23				
Standard deviation	2.26	20.89	4.62	28.01	0.26	1.28				
Max.	21.50	159.90	40.04	220.21	2.78	25.35				
Min.	0.00	0.01	0.00	0.01	0.00	0.01				

Explanations: n = total of data.Source: own study.

Source: own study.

Mean content of N-NH4 in groundwater samples from organic and mineral-organic soil layer were 7.98 and 9.69 mg N-NH₄·dm⁻³, respectively. These concentrations were about 17 and 21 times higher than N-NH4 concentration in surface water from drained ditches and channels. Concentrations of both compounds varied greatly. Furthermore variability coefficient usually exceeded 180% for both kinds of groundwater samples from each control point. Maximum values of P-PO₄ concentration reached 21.50 and 40.04 mg P-PO₄·dm⁻³ in groundwater samples from organic and mineral-organic soil layer, respectively and 2.78 mg $P\text{-}PO_4\text{-}dm^{-3}$ in surface water samples. Maximum values of N-NH4 concentrations were over 5.5 times higher - they reached 159.90, 220.21 and 25.35 mg N-NH₄·dm⁻³, respectively. Therefore, during the entire study period high levels of P-PO₄ and N-NH4 concentration were maintained in tested groundwater considering groundwater quality standards (Tab. 4).

Table 4. Ground water quality classification with limit values for ammonium nitrogen $(N-NH_4)$ and phosphate-phosphorus $(P-PO_4)$

Ground-		Limit values in I–V classes							
water quality index	Unit	I	II	III	IV	v			
N-NH ₄	mg NH₄·dm ^{−3}	0.5	1.0	1.5	3.0	>3.0			
	mg N-NH ₄ ·dm ⁻³	0.389	0.777	1.166	2.331	>2.331			
P-PO ₄	mg PO₄·dm ^{−3}	0.51)	0.51)	1.0	5.0	>5.0			
	mg P-PO ₄ ·dm ⁻³	0.163	0.163	0.326	1.630	>1.630			

¹⁾ There is no sufficient ground for differentiating the limit values in some quality classes; for assessment the class of the highest quality is assumed within the classes having the same limit value. Source: Rozporządzenie ... [2019].

In 21.8% and 23.6% groundwater samples from organic and mineral-organic soil layer, respectively, $P-PO_4$ concentration exceeded the limit value of 1.630 mg $P-PO_4$ ·dm⁻³ for fifth class of groundwater quality, including poor quality waters (Fig. 5). One-third of groundwater samples belonged to the same fifth class of groundwater quality due to N-NH₄ concentration limit reached as well.



Fig. 5. Percentage distribution of groundwater quality in terms of phosphate-phosphorus ($P-PO_4$) and ammonium nitrogen ($N-NH_4$) concentrations; source: own study

Furthermore, surface water pollution by ammonia and phosphate was similar. In more than 30% and 27% of water samples, the concentration of $P-PO_4$ and $N-NH_4$, respectively, exceeded limit values specified for first and second surface water quality class (Tab. 5). For all of three types of analysed waters there was a clear relationship between these nutrients ions. $P-PO_4$ and $N-NH_4$ data was not normally distributed due to random extreme values, so Spearman's rank correlation coefficients were calculated (Tab. 6). The strong correlation with a statistical significance between $P-PO_4$ and $N-NH_4$ concentration in groundwater can be explained by their common origin related to the mineralization process of peat soil organic matter which depends mainly on changes of soil water regime.

Table 5. Percentage distribution of surface water quality with limit values for phosphate-phosphorus $(P-PO_4)$ and ammonium nitrogen $(N-NH_4)$; surface water quality classification for stream or water jet in a valley with large share of peatlands

Quality	Surface water quality	Limit values $(ma_1 dm^{-3})$	Amount/percentage of samples			
index	class	(mg·am)	n	%		
	Ι	≤0.07	385	57.4		
	II	(0.07-0.09>	83	12.4		
11-11114	non-classified waters ¹⁾	>0.09	203	30.3		
	Ι	≤0.14	229	34.1		
P-PO ₄	II	(0.14-0.42>	258	38.5		
	non-classified waters ¹⁾	>0.42	184	27.4		

¹⁾ No limit values.

Source: own study based on Rozporządzenie ... [2021].

Table 6. Coefficients of Spearman's rank correlation (significant at $\alpha = 0.05$) between phosphate-phosphorus (P-PO₄) and ammonium nitrogen (N-NH₄) content in: groundwater from organic soil layer "S", groundwater from mineral-organic soil layer "P" and surface water "C" between 2000 and 2010

Variable	S: N-NH ₄	P: N-NH ₄	C: N-NH ₄
S: P-PO ₄	0.774		
P: P-PO ₄		0.778	
C: P-PO ₄			0.464

Source: own study.

Mean concentrations of P-PO₄ and N-NH₄ at individual water monitoring points varied depending on nutrient ion and water type (Tab. 7). The Kruskal-Wallis test confirmed that differences between them were statistically significant (Tab. 8), which may indicate that water pollution was influenced by local factors. The flow and water storage in soil profile, and thus the flow and storage of nutrients, depends largely on the physical properties of peat soil [REZANEZHAD et al. 2016]. Obtained results have been associated with this phenomenon. Moreover, state of the groundwater contamination may have been influenced by the distance of its monitoring points from the surface water. It results indirectly from the research of KOERSEL-MAN et al. [1993], who found that river water is a factor stimulating the release of P from peat. Furthermore, mean P-PO₄ and N-NH₄ concentrations in groundwater samples collected from organic soil layer decreased with the depth of this layer (Fig. 6). However, this relationship was statistically significant only in case of $P-PO_4$ concentration (Spearman's rho = -0.8117; *p*-value < 0.05). The existence of this correlation can be explained to a certain extent by a laminar structure of peat soils in research area which results in varying sorption properties. Due to the different sorption capacity and strength of P binding in organic formation, the mitigation of inorganic and organic P into the soil profile and the possibility of its release into groundwater had differed [SAPEK 2012]. Moreover, at varied organic levels of soil formations at individual monitoring points there were different storage and water flow conditions which shaped especially the state of decomposition and reduction in the volume (compaction or consolidation process) of deeper parts of soil organic matter [Morris et al. 2015; REZANEZHAD et al. 2016; WORONKO 2008].

The groundwater level in organic soil layer was the factor differentiating the mean P-PO₄ and N-NH₄ concentration in all of three types of water. In most of them, an increasing nutrients concentration trend with a successive decreasing the groundwater level in organic soil layer by 10 cm was found (Fig. 7). In relation to N-NH₄ concentration in groundwater in peat-muck soils, this pattern was also noticed by SZYMCZYK *et al.* [2010]. Based on Kruskal–Wallis test analysis it was shown that there are statistically significant differences in mean P-PO₄ concentrations in groundwater from mineral-organic soil layer and mean N-NH₄ concentrations in all types of studied water in intervals of 10 cm of groundwater level in the organic soil layer (Tab. 9). Therefore, changes in groundwater level in organic soil layer cause changes

^{© 2021.} The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB). This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/3.0/)

	Descriptive	TT 1.	Test stand code								
Type of water	statistics	Unit	K2	K4	K5	K7	K8	К9			
				P-PO ₄							
	п		120	119	110	110	109	101			
Type of water Groundwater from organic soil layer Groundwater from mineral- organic soil layer Groundwater from mineral- organic soil layer Groundwater from organic soil layer Groundwater from organic soil layer Groundwater from organic soil layer Groundwater from mineral- organic soil layer Surface water Surface water	mean		0.97	0.76	1.60	2.01	1.01	1.08			
	median		0.40	0.14	0.31	0.82	0.11	0.19			
	SD	mg P-PO ₄ ·dm ⁻³	1.81	1.62	2.72	2.48	2.59	1.94			
	max.		15.40	12.70	21.50	10.28	20.07	8.67			
	min.		0.01	0.00	0.01	0.03	0.01	0.01			
		n	115	85	77	78	78	75			
Groundwater from mineral-	mean		1.26	0.37	0.49	4.37	1.13	3.81			
	median		0.17	0.12	0.10	1.84	0.07	0.57			
organic soil	SD	mg P-PO ₄ ·dm ⁻³	2.13	0.86	1.08	6.97	2.29	8.08			
layer	max.		9.48	6.02	7.08	35.00	12.75	40.04			
Surface water	min.		0.01	0.00	0.00	0.01	0.01	0.01			
		n	116	112	124	2.48 2.59 1.94 10.28 20.07 8.67 0.03 0.01 0.01 78 78 75 4.37 1.13 3.81 1.84 0.07 0.57 6.97 2.29 8.08 35.00 12.75 40.04 0.01 0.01 0.01 1122 84 113 0.08 0.28 0.13 0.06 0.08 0.05 0.10 0.45 0.27 0.94 2.50 2.15 0.00 0.00 0.01 110 109 101 12.17 9.18 6.77 2.55 0.55 0.73 23.63 26.39 16.34 140.80 156.20 99.98 0.05 0.04 0.01 78 78 75					
Surface water	mean		0.11	0.13	0.08	0.08	0.28	0.13			
	median		0.06	0.07	0.05	0.06	0.08	0.05			
	SD	mg P-PO₄·dm ^{−3}	0.28	0.22	0.13	0.10	0.45	0.27			
	max.		2.78	1.86	1.30	0.94	2.50	2.15			
	min.		0.00	0.00	0.00	0.00	0.00	0.01			
			N-NH ₄								
		n	120	119	110	110	109	101			
	mean		4.28	4.29	11.72	12.17	9.18	6.77			
Groundwater from organic soil layer Groundwater from mineral- organic soil layer Surface water Groundwater from organic soil layer Groundwater from organic soil layer	median		1.26	0.64	1.11	2.55	0.55	0.73			
	SD	mg N-NH₄·dm ^{−3}	12.38	12.94	27.69	23.63	26.39	16.34			
	max.		85.44	84.43	159.90	140.80	156.20	99.98			
	min.		0.04	0.05	0.04	0.05	0.04	0.01			
		n	115	85	77	78	78	75			
	mean		5.77	1.69	2.10	21.68	10.74	19.01			
from mineral-	median		0.95	0.42	0.46	4.04	0.39	1.06			
organic soil	SD	mg N-NH₄·dm⁻³	21.66	4.22	5.62	33.17	32.47	44.26			
layer	max.		188.40	30.76	38.95	126.00	216.50	220.21			
	min.		0.04	0.01	0.01	0.01	0.02	0.01			
		п	116	112	124	122	84	113			
	mean		0.45	0.43	0.31	0.32	0.84	0.60			
Groundwater from organic soil layer Groundwater from mineral- organic soil layer Groundwater from organic soil layer Groundwater from organic soil layer	median		0.19	0.25	0.20	0.19	0.30	0.30			
	SD	mg N-NH₄·dm ^{−3}	1.41	0.51	0.34	0.34	2.85	1.04			
	max.		14.65	3.71	2.01	1.97	25.35	5.78			
	min.		0.01	0.03	0.01	0.01	0.01	0.02			

Table 7. Descriptive statistics of phosphate-phosphorus ($P-PO_4$) and ammonium nitrogen ($N-NH_4$) concentrations in groundwater and surface water for individual test stands

Explanations: SD = standard deviation, n = total of data. Source: own study.

Indicator		Indepen	н	p-value					
		K2	K4	K5	K7	K8	К9		1
	n	115	113	104	103	104	93	53.40	
P-PO ₄ _S	R	39,787	29,025	35,390	41,692	27,120	27,016	52.48	0.0000
	n	110	82	71	71	75	68		
P-PO ₄ _P	R	26,733	16,124	14,466	21,960	14,654	20,067	49.72	0.0000
	n	108	102	103	101	75	90		
P-PO ₄ _C	R	28,007	32,272	28,049	29,007	26,448	24,128	19.41	0.0016
	n	115	113	104	103	104	93		
N-NH ₄ _S	R	38,775	29,719	34,423	40,169	29,088	27,857	33.55	0.0000
	n	110	82	71	71	75	68		
N-NH ₄ _P	R	26,824	15,768	14,449	21,882	15,554	19,527	44.40	0.0000
	n	108	102	103	101	75	90	10.66	0.0000
N-NH ₄ _C	R	27,943	31,068	27,345	26,937	24,716	29,902	18.66	0.0022

Table 8. Kruskal–Wallis analysis for phosphate-phosphorus (P-PO₄) and ammonium nitrogen (N-NH₄) indicators related to water sampling place

Explanations: n = total of data, R = rank sum, H = Kruskal-Wallis test value, p-value – significance level; $P-PO_4_S/N-NH_4_S = \text{concentration}$ of nutrient ions in groundwater from organic soil layer; $P-PO_4_P/N-NH_4_P = \text{concentration}$ of nutrient ions in groundwater from mineral-organic soil layer; $P-PO_4_C/N-NH_4_C = \text{concentration}$ of nutrient ions in surface water; in bold – statistically significant. Source: own study.



Fig. 6. The relationship between the depth of organic soil layer and the phosphate-phosphorus $(P-PO_4)$ and ammonium nitrogen $(N-NH_4)$ concentration in groundwater from this layer at individual test stands; source: own study

in the concentration of one or two analysed ions in each type of water. It can be concluded that there were vertical and horizontal flow processes, and more precisely – groundwater-groundwater and groundwater-surface water connectivity. Presence of these

interactions facilitated migration and exchange of P-PO4 and N-NH₄ between different types of water. Levels of nutrient ions concentrations in groundwater in organic soil layer, as well as the dynamics of their changes, were related to a set of various environmental and economic factors (such as: rainfall, local soil specificity, irrigation, doses of P and N fertilizers, organic fertilizers application) and soil P and N cycle. Undoubtedly, cycle of P and N in peat soil from research area largely shaped the process of SOM mineralization which leads to the release of N and P mineral forms and affects the ground and surface water quality. And furthermore, the groundwater level has a significant impact on the rate of nutrient release in peat soils too [KOERSELMAN et al. 1993]. With the lowering of the groundwater table, the rate of peat soil mineralization accelerates [METTROP et al. 2014; TUUKKANEN et al. 2017] and the concentration of soluble P and N forms in it increases [SAPEK 2010]. With this in view, it should be stressed that the groundwater level in peat soils and the amount of mineralized N and P can be influenced by controlling the water level in drainage ditches. Skillful use of such type of control is important, among others, in terms of reducing surface water pollution by nutrients. Within this scope, VAN BEEK et al.'s [2007] studies conducted in the Netherlands have shown, that increasing groundwater level by 20 cm in drainage crossing grassland led to 30% decrease in N load introduced into it.





Fig. 7. Mean concentration of ammonium nitrogen (N-NH₄) and phosphate-phosphorus (P-PO₄) in each type of studied water in separated 10 cm intervals of groundwater level in organic soil layer; source: own study

Indica	tor	Independ	Independent (grouping) variable: groundwater table in "S" well used for water sampling from organic soil layer (cm)										p-value
		<10	(10-20>	(20-30>	(30-40>	(40-50>	(50-60>	(60-70>	(70-80>	(80-90>	(90-100>		1
	n	28	31	56	83	114	110	113	62	23	12		0.051
P-PO ₄ _S	R	8,754	9,884	16,209	26,052	34,359	35,612	34,900	24,552	6,499	3,211	15.83	0.071
	n	20	24	47	69	88	91	83	35	15	5	20.54	
P-PO ₄ _P	R	3,924	4,372	12,107	18,960	18,820	22,463	19,947	9,698	2,687	1,027		0.015
	n	27	30	52	79	106	102	100	55	22	6	8.60	0.154
P-PO ₄ _C	R	7,735	7,392	14,701	20,857	30,631	30,512	29,778	18,381	6,356	1,569		0.476
	n	28	31	56	83	114	110	113	62	23	12	18.79	
N-NH ₄ S	R	8,351	9,978	16,736	25,703	33,726	35,141	34,651	25,290	6,669	3,787		0.027
	п	20	24	47	69	88	91	83	35	15	5	19.75	
N-NH ₄ _P	R	4,101	4,401	12,471	19,284	18,943	22,039	19,557	9,393	2,738	1,079		0.020
	п	27	30	52	79	106	102	100	55	22	6	17.22	
N-NH ₄ _C	R	7,394	9,797	15,738	22,067	28,106	27,743	28,388	18,258	7,821	2,601		0.046

Table 9. Kruskal–Wallis test analysis for phosphate-phosphorus ($P-PO_4$) and ammonium nitrogen ($N-NH_4$) $P-PO_4$ and $N-NH_4$ indicators related to groups distinguished by the groundwater level in organic soil layer

Explanations as in Tab. 8.

Source: own study.

CONCLUSIONS

The results of eleven-year-long studies of P-PO4 and N-NH4 concentrations in groundwater from a meadow complex located on peat soils showed mostly high content of both nutrient ions. In the water from organic soil layer the highest concentrations of P-PO₄ and N-NH₄ reached the level of 22 and 160 mg \cdot dm⁻³ while in water from mineral-organic soil layer they exceeded values of 22 and 160 mg·dm⁻³, respectively. In surface water the highest recorded nutrient ions concentrations were much lower - close to 2.8 mg P-PO4·dm⁻³ and 25 mg N-NH4·dm⁻³. Due to P-PO4 and N-NH₄ concentrations, about 46 and 39% of water samples from organic soil layer and more than 40 and 37% of water samples from mineral-organic soil layer, respectively, were characterized by poor chemical status which includes IV-V groundwater quality classes. At the same time, due to the exceeding of the limit values of P-PO₄ and N-NH₄ concentrations, water samples from watercourses in over 30 and 27%, respectively, were not within 1st and 2nd class of surface water quality.

The concentrations of P-PO₄ and N-NH₄ were significantly positively correlated with each other which can be associated with the release of accumulated amounts of P and N into soil solution and groundwater as a result of decomposition of peat organic matter. In the spatial arrangement, a set of results of P-PO₄ and N-NH₄ concentration in ground- and surface water was characterized by a considerable diversity. This suggests that the contamination of water bodies with P-PO₄ and N-NH₄ was influenced by site-specific factors, especially the physical properties of peat. Moreover, the thickness of organic soil layer had a significant influence on P-PO₄ formation and concentration in groundwater from this layer.

The groundwater level depths in organic soil layer considered in separated 10 cm intervals was a factor determining the changes of analysed ions in all selected water types. In this regard, it was found that the average groundwater level in organic soil layer had a statistically significant impact on the mean P-PO₄ concentration in groundwater associated with mineral-organic soil layer and on the mean N-NH₄ concentration in each type of water. It was also reported that the trend of P-PO₄ concentration values in all types of water was increasing with the groundwater table in organic soil layer decreasing every 10 cm. A course of changes in N-NH₄ concentration values was similar in relation to groundwater in organic soil layer and surface water.

In conclusion, obtained research results show that in the studied area of grasslands located on peat-muck soils:

- relatively high levels of P-PO₄ and N-NH₄ were permanently sustained in ground and surface water;
- P-PO₄ and N-NH₄ concentrations in groundwater were correlated with each other, which indicates that the peat mineralization process is common cause for their origin;
- concentrations of P-PO₄ and N-NH₄ in analysed waters were spatially diversified, which suggests that they were formed under locally different conditions;
- in general, the concentrations of P-PO₄ and N-NH₄ in ground and surface water increased along with a decreasing level of groundwater deposition.

REFERENCES

- JASZCZYŃSKI J. 2010. Rozpuszczalny węgiel organiczny w wodach siedlisk torfowych [Dissolved organic carbon in waters from peatlands]. PhD Thesis. Falenty. ITP p. 26–27.
- JASZCZYŃSKI J. 2015. The relationship between dissolved organic carbon and hydro-climatic factors in peat-muck soil. Journal of Water and Land Development. No. 24 (I–III) p. 27–33. DOI 10.1515/ jwld-2015-0004.
- KOERSELMAN W., VAN KERKHOVEN M.B., VERHOEVEN J.T. 1993. Release of inorganic N, P and K in peat soils; effect of temperature, water chemistry and water level. Biogeochemistry. Vol. 20 p. 63–81. DOI 10.1007/BF00004135.
- KOLENBRANDER G.J. 1972. The eutrophication of surface water by agriculture and the urban population. Stikstof. No. 15 p. 56–67.
- LAINE M.P.P., STRÖMMER R., ARVOLA L. 2013. Nitrogen release in Pristine and drained peat profiles in response to water table fluctuations: A Mesocosm experiment. Applied and Environmental Soil Science. Vol. 2013. DOI 10.1155/2013/694368.
- LITAOR M. I., REICHMANN O., BELZER M., AUERSWALD K., NISHRI A., SHENKER M. 2003. Spatial analysis of phosphorus sorption capacity in a semiarid altered wetland. Journal of Environmental Quality. Vol. 32 p. 335–343. DOI 10.2134/jeq2003.3350.
- LUCASSEN E., SMOLDERS A. J. P., LAMERS L. P. M., ROELOFS J. G. M. 2005. Water table fluctuations and groundwater supply are important in preventing phosphate-eutrophication in sulphate-rich fens: Consequences for wetland restoration. Plant and Soil. Vol. 269(1) p. 109–115. DOI 10.1007/s11104-004-0554-3.
- MARTIN H.W., IVANOFF D.B., GRAETZ D.A., REDDY K.R. 1997. Water table effects on histosol drainage water carbon, nitrogen, and phosphorus [online]. Journal of Environmental Quality. Vol. 26 p. 1062–1071. [Access 23.09.2021]. Available at: https://soils.ifas. ufl.edu/wetlands/publications/PDF-articles/218.Water%20table% 20effects.pdf
- MEISSNER R., LEINWEBER P. 2004. PROWATER: Prevention of diffuse water pollution with phosphorus from degraded and re-wetted peat soils [online]. Final Report of an European Research Project. UFZ-Report 5/2004. Leipzig. UFZ. [Access 23.09.2021]. Available at: https://www.ufz.de/index.php?en=20939&pub_id=4342
- MEISSNER R., RUPP H., LEINWEBER P. 2003. Re-wetting of fen soils and changes in water quality – experimental results and further research needs. Journal of Water and Land Development. Vol. 7 p. 75–91.
- METTROP I.S., CUSELL C., KOOIJMAN A.M., LAMERS L.P.M. 2014. Nutrient and carbon dynamics in peat from rich fens and Sphagnum-fens during different gradations of drought. Soil Biology and Biochemistry. Vol. 68 p. 317–328 DOI 10.1016/j.soilbio.2013 .10.023.
- MORRIS P.J., BAIRD A.J., BELYEA L.R. 2015. Bridging the gap between models and measurements of peat hydraulic conductivity. Water Resources Research. Vol. 51(7) p. 5353–5364. DOI 10.1002/ 2015WR017264.
- RENGER M., WESSOLEK G., SCHWÄRZEL K., SAUERBREY R., SIEWERT C. 2002. Aspects of peat conservation and water management. Journal of Plant Nutrition and Soil Science. Vol. 165 p. 487–493. DOI 10.1002/1522-2624(200208)165:4<487::AID-JPLN487>3.0.CO;2-C.
- REZANEZHAD F., PRICE J. S., QUINTON W. L., LENNARTZ B., MILOJEVIC T., VAN CAPPELLEN P. 2016. Structure of peat soils and implications for water storage, flow and solute transport: A review update for geochemists. Chemical Geology. Vol. 429 p. 75–84. DOI 10.1016/ j.chemgeo.2016.03.010.
- Riddle M., Bergström L., Schmieder F., Kirchmann H., Condron L., Aronsson H. 2018. Phosphorus leaching from an organic and

a mineral arable soil in a rainfall simulation study. Journal of Environmental Quality. Vol. 47 p. 487–495. DOI 10.2134/ jeq2018.01.0037.

- ROBINSON J.A., JOHNSTON C.T., REDDY K.R. 1998. Combined chemical and 31P-NMR spectroscopic analysis of phosphorus in wetland organic soils [online]. Soil Science. Vol. 163 p. 705–713. [Access 23.09.2021]. Available at: https://soils.ifas.ufl.edu/wetlands/publications/PDF-articles/234.Combined%20chemical.pdf
- Rozporządzenie Ministra Gospodarki Morskiej i Żeglugi Śródlądowej z dnia 11 października 2019 r. w sprawie kryteriów i sposobu oceny stanu jednolitych części wód podziemnych [Regulation of the Minister of Maritime Economy and Inland Navigation of October 11, 2019 on the criteria and method of assessing the state of groundwater bodies] [online]. [Accesss 23.09.2021]. Available at: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU201 90002148/O/D20192148.pdf
- Rozporządzenie Ministra Infrastruktury z dnia 25 czerwca 2021 r. w sprawie klasyfikacji stanu ekologicznego, potencjału ekologicznego i stanu chemicznego oraz sposobu klasyfikacji stanu jednolitych części wód powierzchniowych, a także środowiskowych norm jakości dla substancji priorytetowych [Regulation of the Minister of Infrastructure of June 25, 2021 on the classification of ecological status, ecological potential and chemical status and the method of classification of the state of surface water bodies, as well as environmental quality standards for priority substances] [online]. [Access 8.12.2021]. Available at: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU2021 0001475/O/D20211475.pdf
- RUPP H., MEISSNER R., LEINWEBER P. 2004. Effects of extensive land use and re-wetting on diffuse phosphorus pollution in fen areasresults from a case study in the Droemling catchment, Germany. Journal of Plan Nutrition and Soil Science. Vol. 167 p. 408–416. DOI 10.1002/jpln.200421395.
- SAPEK A., SAPEK B. 1997. Metody analizy chemicznej gleb organicznych [Methods of chemical analysis of organic soils]. Materiały Instruktażowe. Nr 115. Falenty. IMUZ p. 80–81.
- SAPEK B. 2010. Uwalnianie azotu i fosforu z materii organicznej gleby [Nitrogen and phosphorus release from soil organic matter] [online]. Woda-Środowisko-Obszary Wiejskie. T. 10. Z. 3(31) p. 229–256. [Access 23.09.2021]. Available at: https://www.itp. edu.pl/old/wydawnictwo/woda/zeszyt_31_2010/artykuly/Sapek% 20B.pdf
- SAPEK B. 2012. Phosphorus sorption properties of deposits from peatmuck soil profile in the Kuwasy object. Journal of Water and Land Development. No. 16 (I–VI) p. 61–66. DOI 10.2478/v10025 -012-0026-8.
- SAPEK B. 2014. Nagromadzenie i uwalnianie fosforu w glebach źródła, procesy, przyczyny [Soil phosphorus accumulation and release – sources, processes, causes] [online]. Woda-Środowisko-Obszary Wiejskie. T. 14. Z. 1(45) p. 77–100. [Access 23.09.2021]. Available at: http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.baztech-9f4164ab-93ec-4f19-b39a-433a3dafb42a
- STEENVOORDEN J.H.A.M. 1976. Nitrogen, phosphate and biocides in groundwater as influenced by sol factors and agriculture. Wageningen. Institute for Land and Water Management Research. Technical Biuletin. No. 97 p. 53–69.
- SZYMCZYK S., PAWLACZUK J.L., STĘPIEŃ A. 2010. Seasonal variability of mineral nitrogen in groundwater of hydrogenic soils. Journal of Elementology. Vol. 15(4) p. 713–723. DOI 10.5601/jelem.2010 .15.4.713-723.
- TUUKKANEN T., MARTTILA H., KLØVE B. 2017. Predicting organic matter, nitrogen, and phosphorus concentrations in runoff from peat

This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/3.0/)

extraction sites using partial least squares regression. Resource Research. Vol. 53 p. 5860-5876. DOI 10.1002/2017WR020557.

- WORONKO D. 2008. Diagnoza zmienności cech fizycznych i geochemicznych Wielkiego Torfowiska Batorowskiego w Górach Stołowych [Variablity diagnosis of physical and geochemical properties of Wielkie Torfowisko Batorowskie peatland in Stołowe Mountains] [online]. Przegląd Geofizyczny. T. 53. Z. 2 p. 181–194. [Access 23.09.2021]. Available at: http://ptgeof. imgw.pl/?strona=5,9,2
- VAN BEEK C.L., DROOGERS P., VAN HARDEVELD H.A., VAN DEN EERTWEGH G. A.P.H., VELTHOF G.L., OENEMA O. 2007. Leaching of solutes from

an intensively managed peat soil to surface water. Water, Air & Soil Pollution. Vol. 182 p. 291–301. DOI 10.1007/s11270-007-9339-7.

- VENTERINK H. O., DAVIDSSON T. E., KIEHL K., LEONARDSON L. 2002. Impact of drying and rewetting on N, P and K dynamics in a wetland soil. Plant Soil. Vol. 243 p. 119–130. DOI 10.1023/ A:1019993510737.
- ZAK D., GELBRECHT J., STEINBERG C.E.W. 2004. Phosphorus retention at the redox interface of peatlands adjacent to surface waters in northeast Germany. Biogeochemistry. Vol. 70 p. 357–368. DOI 10.1007/s10533-003-0895-7.