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Ecohydrological role of groundwater outflows in the functioning of the ecotone zone in Lake Jaczno, Poland

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Highlights

- Headwater peatlands are crucial for lake's ecotone as they providing ecological services.
- The headwater peatland contributes to the lake's low trophic status.
- The lacustrine ecotone is hydrologically stable during the vegetation season.
- Clay deposits restrict the exchange of water between groundwater and lake water.

Abstract: The research determined the influence of natural groundwater outflows from the spring peat bog on the water supply and its quality in Lake Jaczno. Lake Jaczno is located in the Suwalski Landscape Park (SLP) in the Podlaskie Voivodeship, north-east Poland. The research was conducted from April 2009 to October 2010 and from September 2022 to September 2023. Water samples were collected from spring areas, shallow groundwater, and from Lake Jaczno. Fieldwork involved measuring flow, temperature, water electrolytic conductivity (*EC*), dissolved oxygen (DO) concentration, water oxygen saturation (*WS*), and water reaction (pH). Chemical analyses of water samples were carried out in the laboratory. Findings indicate that groundwater, spring water, and lake water in the SLP maintain high quality, with no significant changes in chemical composition over the past decades. Additionally, the physical water parameters display low temporal variability. The *EC* in the tested waters oscillates around 500 $\mu S \cdot cm^{-1}$. Both spring and lake waters are well oxygenated (97–100%). Biogenic element concentrations exhibit higher variability, influenced by flora development in areas with natural groundwater outflows. High oxygenation of water contributes to increased concentrations of nitrates. The analysed waters exhibited similarity in the concentration and structure of phosphorus forms. Additionally, sediment chemical parameters at Lake Jaczno suggests a buffering capacity in the transitional zones between water and land. Despite similarities in chemical composition, sediment granulometry suggests low permeability, potentially restricting exchange between groundwater and surface waters. Monitoring springs in these environments is important due to their impact on quantity and quality of water in the analysed areas.

Keywords: groundwater, headwater peatland, hydrogeology dynamics, lake-land ecotone, springs, water quality

INTRODUCTION

Lake aquatic-terrestrial ecotones are characterised by the coexistence of terrestrial and aquatic ecosystems, potentially introducing stress factors that influence plant growth. Due to high temperatures in summer, vegetation in the lakeside ecotone regenerates quickly, with its peak growth at the end of the summer season (Dai *et al.*, 2003). During this period, vegetation absorbs and binds large amounts of nutrients from the soil and water. Lake ecotones act as natural filters, reducing pollution and supporting filtration processes. Biological and chemical processes within the ecotone impact the balance of the aquatic ecosystem and play a significant role in sustaining biodiversity (Ward and Tockner, 2001). Changes in water levels can alter redox conditions in lake ecotones. Inundation may increase nutrient levels in the reservoir, potentially becoming a source of pollution and deteriorating water quality. However, at high water levels, the denitrification rate increases with the intensity of the inundation (Arif *et al.*, 2022). In regions characterised by zones with natural groundwater outflows rich in carbonate compounds, a distinctive type of peat-forming ecosystem known as headwater peatlands emerges (Hillbricht-Ilkowska and Węgleńska, 2001). In the ecotone of a lake, headwater peatlands form through the accumulation of organic material in spring areas. The process begins with the growth of peat-forming vegetation, contributing to the development of an organic layer (Mazurek, Kruszyk and Szpikowska, 2014). Continuous groundwater supply restricts the complete decomposition of organic matter, leading to the gradual accumulation of peat. Headwater peatlands are vital to the lake's ecotone, providing numerous ecological services. The formation and significance of headwater peatlands in the lake's ecotone highlight their crucial role in maintaining environmental balance, regulating water flow, supporting biodiversity, and contributing to global climate change mitigation efforts (Krepski, Kuczyńska and Czerniawski, 2023).

Sites of headwater peatlands are known from many regions of Poland, including north-east Poland, although they are not subject to monitoring research in these areas. This article explores the significance of groundwater outflows in the ecotone zone of Lake Jaczno and their impact on the overall ecological balance. The primary objective was to assess the stability of the habitat within the ecotone (headwater zone) and describe hydrological and hydrochemical relationships between different aquatic environments. The article presents the following research hypotheses:

1) concentrated water outflows from the headwater peatland play a significant role in Lake Jaczno's water supply;
2) concentrated water outflows from the headwater peatland are one of factors contributing to the low trophic status of Lake Jaczno;
3) similarity in chemical composition implies the existence of hydraulic connectivity between groundwater and surface water in the headwater peatland.

MATERIALS AND METHODS

The research focused on the Suwalski Landscape Park (SLP) (Fig. 1), located in the northern part of the Podlaskie Province. The study focused on the environmentally valuable headwater zone at Lake Jaczno within the protected area. The SLP safeguards a unique post-lacustrine landscape developed during the Vistula Glaciation (Ber, 2000). It is located in the catchments of the Czarna Hańcza and Szeszupa Rivers, both belonging to the Neman River catchment area. The lakes and rivers of the SLP have been relatively thoroughly described in terms of their hydrological, hydrochemical, and ecological characteristics (Grabowska, Konecka and Górniak, 2006; Zieliński, Kłoczewska and Górniak, 2006; Jekatierynczuk-Rudczyk *et al.*, 2012; Jeaktierynczuk-Rudczyk, 2014). Natural groundwater outflows in the area have been studied sporadically, with particular focus on their impact on environmental biodiversity (Buczyński *et al.*, 2007).

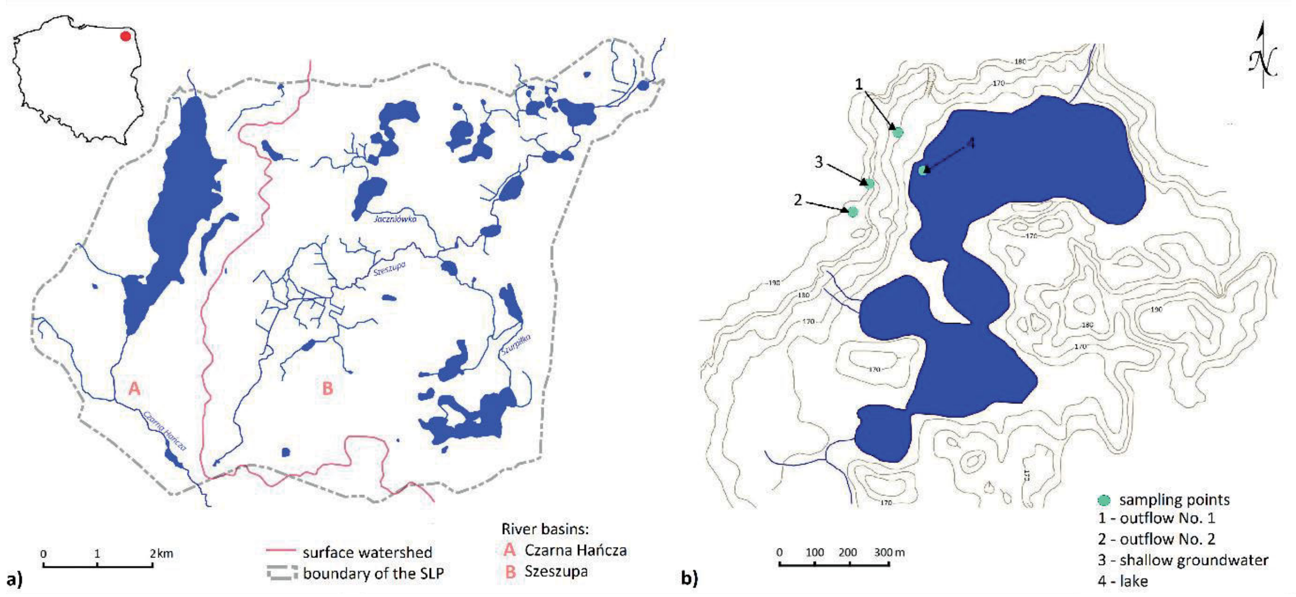

Fig. 1. Location of lakes in the Suwalski Landscape Park (SLP) against: a) hydrographic division, b) the location of sampling points at Lake Jaczno; source: own elaboration

Lake Jaczno is located in a deep marginal valley in the northern part of the park (Fig. 1a). It is a flow-through lake in the Jacznica (Jaczniówka) River valley, flowing into the Szeszupa River. Jaczno is considered one of the largest lakes in the SLP, with its surface area of 41 ha, mean depth of 11.7 m, and a volume of 4,797 km^3. The direct catchment of Lake Jaczno is mainly forested, with small sections used for agriculture. No sources of direct water pollution have been recorded in the area.

High land denivelations near the lake contribute to the formation of suspended headwater peatlands (Łoszewski, 2008). Natural groundwater outflows sustain these peatlands at an elevation of 180 m a.s.l., creating a headwater zone. The Lake Jaczno groundwater outflows, classified as sub-slope outflows, drain Quaternary aquifers. Geomorphologically, these outflows exhibit variability, transitioning from rheocrenes to helocrenes within the suspended peatland development area, and then reverting back to rheocrenes at the outflow concentration point. This variation in outflow characteristics over a short distance supports diverse microhabitats, promoting increased regional biodiversity (Buczyński *et al*., 2007).

The research was conducted from April 2009 to October 2010 and from September 2022 to September 2023. Water samples were collected from spring areas (2009–2010, 2022–2023) – Figure 1b, points No. 1 and No. 2, shallow groundwater using a permanent piezometer (2009–2010) – Figure 1b, point No. 3), and from Lake Jaczno (2009–2010, 2022–2023) – Figure 1b, point No. 4. Fieldwork included flow measurements using an electromagnetic OTT meter, as well as measuring temperature, water electrolytic conductivity (*EC*), dissolved oxygen (DO) concentration, water oxygen saturation (*WS*), water reaction (pH), and water redox potential (*Eh*) using a multiparameter probe from HACH. Chemical water analyses were carried out in the laboratory using ISO-standardised methods (Rice *et al.* (eds.), 2012), and covered ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), soluble reactive phosphorus (SRP), dissolved phosphorus (DP), and total phosphorus (TP). Kjeldhal nitrogen (KN) was determined using a Kjeldhal analyser, and total inorganic nitrogen (TIN) concentration was calculated as NH_4-N plus NO_3-N. Total organic nitrogen (TON) was derived from the difference between KN and -NH_4-N . Total nitrogen (TN) was calculated as the sum of TON and TIN. Total organic carbon (TOC) and dissolved organic carbon (DOC) were measured with a Shimadzu TOC – 5050A analyser. Iron fractions were determined using 1.10-phenanthroline and manganese in formaldoxime, distinguishing five fractions of phosphorus, iron, and manganese (Cudowski and Górniak, 2008). Trophic state index (*TSI*) was calculated using the method of Carlson (1977), Kratzer and Brezonik (1981), and Dunalska (2009).

Granulometric groups of analysed sediment formations were determined based on fractional composition. Sediment analyses in the ecotone zone included water content (*W*), granulometric composition by the aerometric Prószyński method, active and passive acidity, hydrolytic acidity, cation exchange capacity (*CEC*), potential sorption capacity (*PSC)*, saturation of the sorptive complex with alkaline (*SSC*), organic carbon content (*OCC*) (Tűrin's method), and concentrations of calcium, magnesium, iron, phosphorous, and nitrogen (Ostrowska, Gawliński and Szczubiałka, 1991). The accuracy of water analysis and calculations, including the saturation index (*SI*) of inorganic compounds, was assessed using the PHREEQC Interactive 2.15.

RESULTS

In April 2009, the total yield of all the natural groundwater outflows feeding Lake Jaczno in the north-western part amounted to 88.14 $dm^3 \cdot s^{-1}$. Water flowing from the aquifer was distributed over a distance of 750 m, and eventually, in the place of concentrated outflow, its quantity was considerably lower. On the western slope, places were found with more efficient and concentrated outflow (outflow No. 1) – Figures 1b and 2a. The variability of discharge efficiency in subsequent years was small and did not exceed 10% (Fig. 2a), which indicates the stability of the ecotone zone habitat. The highest alimentation of the suspended peatland with groundwater occurs on this side (Fig. 2b). The effects of higher precipitation are indicated by the peak in the curve in Figure 2c. The average discharge of outlet No. 1 in October 2009 was 32.1 $dm^3 \cdot s^{-1}$ (range: 14.3–58.2 $dm^3 \cdot s^{-1}$), of outlet No. 2 – 3.5 $dm^3 \cdot s^{-1}$ (range: 0.9–6.2 $dm^3 \cdot s^{-1}$) – Figure 2a.

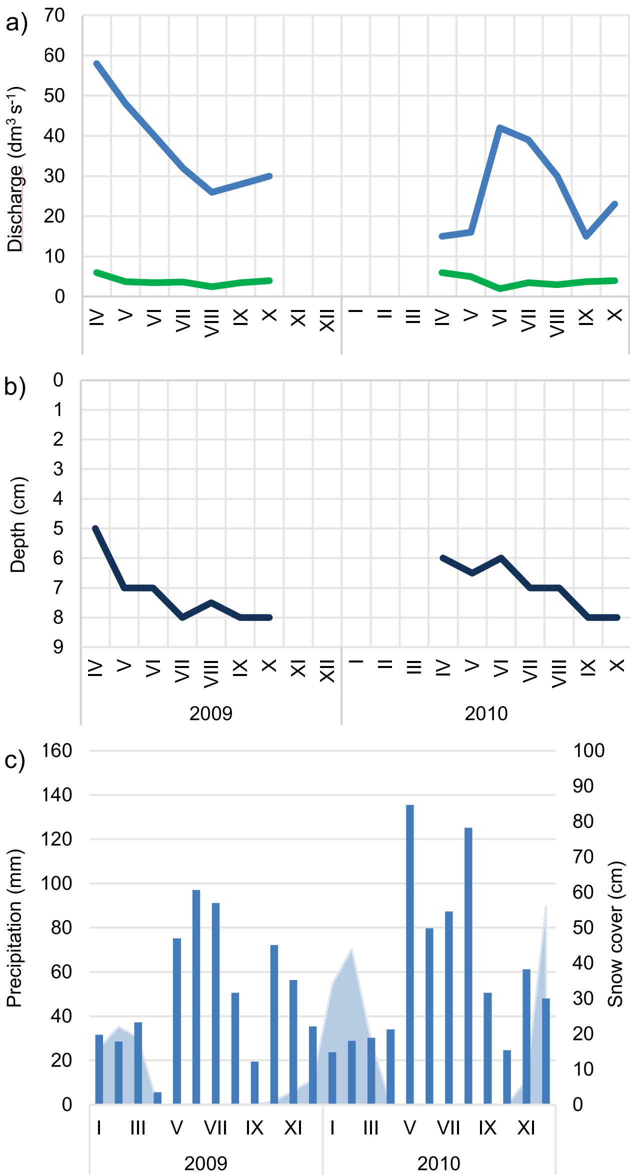

Fig. 2. Groundwater fluctuations over Jaczno in 2009/2010: a) spring discharge; b) groundwater table depth; c) meteorological conditions, including precipitation and snow cover; source: own study

The variability of discharge over time in both tested SPK outflows was similar (spring No. 1 – CV = 38%, spring No. 2 – CV = 36%). The changes in the position of the shallow groundwater table in the piezometer were also minor. The groundwater table was located at a depth of 5–8 cm (Fig. 2b). The coefficients of variation for the shallow groundwater table position were 13%.

The deposits in the ecotone zone above Lake Jaczno consist of clayey sands and sandy loams (Tab. 1). In the headwater peatland, sediments exhibit high water content, exceeding 40%, which confirms the ongoing peat-forming process. At Lake Jaczno, sediments in the ecotone zone exhibit a neutral or slightly alkaline reaction and demonstrate uniform vulnerability to acidification. The saturation of total alkaline cations is high, exceeding 85% of the sorptive complex (Tab. 2). The chemical composition of sediments shows minimal spatial variation (Tab. 3).

Water temperature fluctuations in the lake exceed those observed in the outflow and shallow groundwater. Shallow groundwater exhibits notably lower oxygen levels (4.5 mg·dm^{-3} – Table 4), along with a threefold increase in water colour intensity (30 mg Pt·dm^{-3}). These findings imply periodic oxygen deficiencies and redox conditions influencing mineral dissolution and precipitation. The lake had the lowest concentration of calcium ions, bicarbonates, and silicates. Conversely, shallow groundwater exhibited the highest concentrations of calcium ions (averaging 125 mg·dm^{-3}), while springs demonstrated elevated magnesium ion concentrations (averaging 30.6 mg·dm^{-3}).

The analysed waters showed similarities in the concentration and structure of phosphorus forms (Fig. 3a). In all of the water types, organic nitrogen was the dominant form of nitrogen (Fig. 3b). The concentration of NO_3-N showed statistical variability, with its content in the headwaters approximately three times higher than in groundwater and lake waters (Fig. 3b). Maximum values of TOC and DOC were observed in shallow groundwater (TOC = 17.7 mg C·dm^{-3}; DOC = 11.4 mg C·dm^{-3}). The trophic state index in Lake Jaczno ranged from 46 to 53, indicating mesotrophy.

Table 1. Grain size composition of sediments in the peat bogs of springs in Lake Jaczno

Outflow	Nominal grain size (mm)									Grain size[1)]
	2.00–1.00	1.00–0.50	0.50–0.25	0.25–0.1	0.1–0.05	0.05–0.02	0.02–0.005	0.005–0.002	<0.002	
No. 1	3.0	17.8	11.4	33.0	12.0	13.0	4.0	2.0	5.0	clayey sand
No. 2	0.3	8.4	12.1	28.3	11.0	12.0	8.0	1.0	10.0	sandy loam

[1)] Fractions and granulometric groups were determined according to the division of the Polish Soil Science Society in force until 2008 (Mocek, Drzymała and Maszner, 1997; Zawadzki, 1999).
Source: own study.

Table 2. Attributes of chemical deposits in the ecotone zones within the Suwalski Landscape Park

Outflow	W (%)	pH_{H2O}	pH_{KCl}	Ha	CEC	PSC	SSC (%)
				me·(100 g)$^{-1}$			
No. 1	41.2	7.59	7.55	6.00	46.2	52.20	88.5
No. 2	17.8	7.66	7.44	5.25	46.8	52.05	89.9

Explanations: W = water content, Ha = hydrolytic acidity, CEC = cation exchange capacity, PSC = potential sorption capacity, and SSC = saturation of the sorption complex with alkaline.
Source: own study.

Table 3. The content of elements in the sediments of the Lake Jaczno ecotone in Suwalski Landscape Park

Outflow	OCC	Fe	P	N	Ca	Mg
	% DM					
No. 1	3.90	1.14	0.021	0.33	0.42	0.20
No. 2	3.18	0.85	0.017	0.20	0.77	0.27

Explanations: OCC = organic carbon content, DM = dry matter.
Source: own study.

Table 4. Physical parameters of shallow groundwater, outflows, and Lake Jaczno for 2009/2010 and 2022/2023 (average, standard deviation, and range for pH values)

Specification	N	Temperature (°C)	EC (µS·cm^{-1})	pH	DO (mg·dm^{-3})	WS (%)	Eh (mV)
Shallow groundwater (2009/2010)	7	12.6 ±3.8	641 ±50	7.4–8.3	4.46 ±2.25	46 ±29	174 ±120
Outflows (2009/2010)	7	10.6 ±2.3	536 ±32	7.4–8.4	10.7 ±0.8	102 ±9	162 ±70
Outflows (2022/2023)	6	17.6 ±5.8	438 ±49	6.1–6.8	8.89 ±1.40	97 ±12	212 ±17
Lake (2009/2010)	7	17 ±5.5	416 ±19	7.7–8.5	9.93 ±0.44	105 ±11	147 ±79
Lake (2022/2023)	6	11.6 ±1.7	489 ±25	6.0–6.9	10.45 ±0.21	98 ±3	210 ±20

Explanations: N = number of samples, EC = electrolytic conductivity, DO = dissolved oxygen, WS = water oxygen saturation, Eh = water redox potential.
Source: own study.

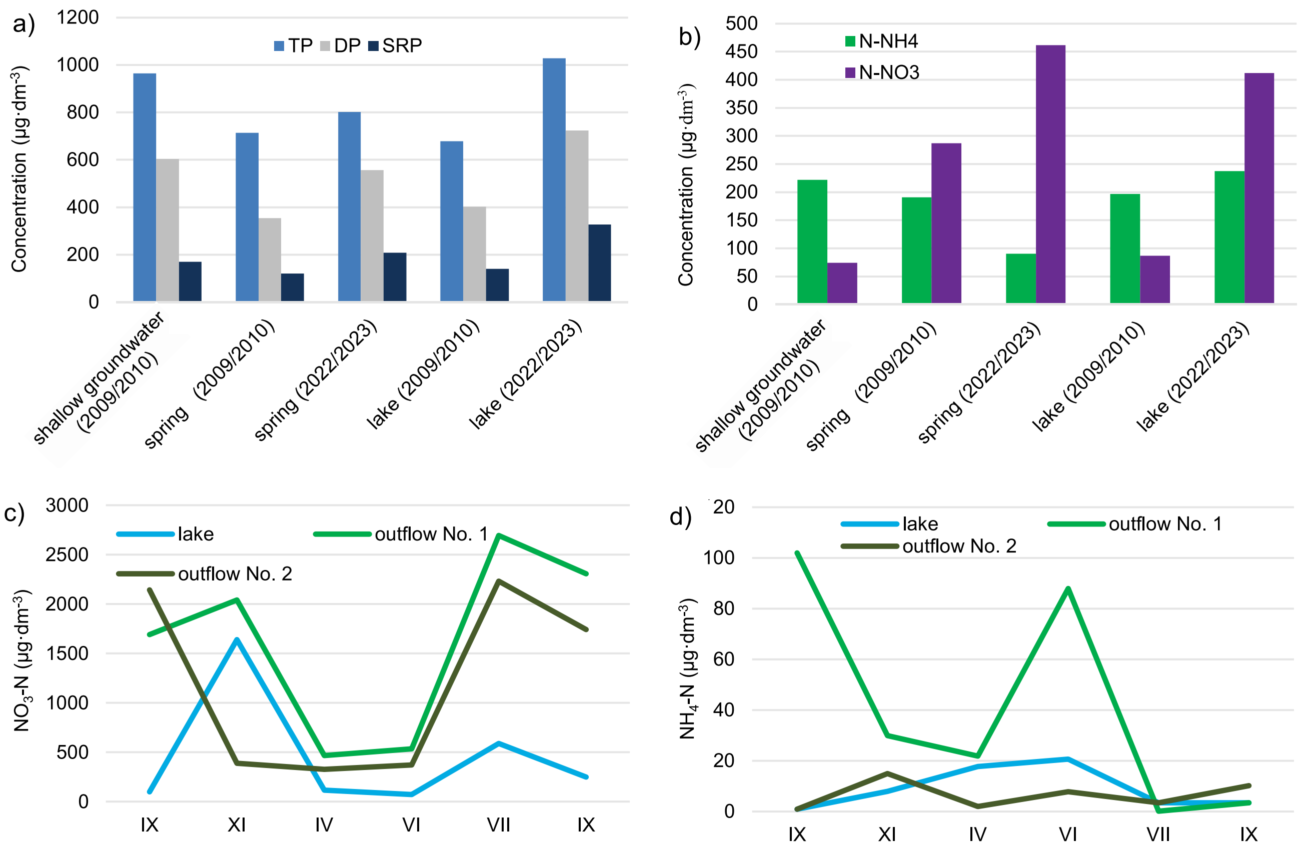

Fig. 3. Concentration of: a) total phosphorus (TP), dissolved phosphorus (DP), and soluble reactive phosphorus (SRP), b) nitrogen forms: ammonium (NH_4-N) and nitrate (NO_3-N) ions, c) seasonal dynamics of NO_3-N, d) seasonal dynamics of NH_4-N; source: own study

DISCUSSION

Headwater areas fed by groundwaters constitute the transitional zone between spatially dispersed processes of the slope system and linear fluvial processes (Richardson and Danehy, 2007). Their role in the development of the environment is considerable. These areas are zones of modern morphological surface degradation (Mazurek, 2008), leading to the diversification of the Young Glacial relief.

The discharge of headwaters and its temporal variability in Polish lakelands is diverse (Jokiel and Michalczyk, 2019). The total discharge of groundwater outflows from the exposed aquifer at Lake Jaczno is estimated to be more than 100 $dm^3 \cdot s^{-1}$ (Łoszewski, 2008). In our studies, we obtained similar results (88.14 $dm^3 \cdot s^{-1}$). When compared to the capacity of Lake Jaczno basin (4,797 km^3), this discharge shows that headwater zones supply 0.16% of the total volume of water accumulated in the lake in one day. Although the daily water supply from the headwater zones seems low, on an annual scale, their contribution increases to almost 58%. This suggests that headwater zones play a very important role in the alimentation of Lake Jaczno, determining stable hydrological and hydrochemical conditions in the lake (Jekatierynczuk-Rudczyk, 2014; Szczucińska, Marciniak and Płocienniczak, 2019). The hydrologically analysed habitat of the SPK is stable, as indicated by the small variability in discharge efficiency during the growing season.

Snow melting in spring contributes to intensive water infiltration into the saturation zone and increases spring water runoff. The minimal changes in shallow groundwater tables suggest high stability of the water relations in the Suwałki Region (Jekatierynczuk-Rudczyk, 2014). The relative strength of shallow groundwater table and yield of outflows suggest the relationship between shallow aquifers and confined waters in the Quaternary aquifer, which occurs on the plateau at a depth of several tens of meters below ground level (PIG, 2004). Hydrological measurements and observations confirm minor changes in water circulation patterns in the Suwałki Region (Puczko, 2024).

An important characteristic of the chemical composition in natural groundwater outflows, groundwater, and surface waters within the SLP is the dominance of bicarbonate ions among anions and calcium and magnesium ions among cations. This ion composition facilitates the formation of carbonate sediments in areas where groundwater drains into Lake Jaczno, establishing the foundation for a valuable and rare natural habitat hosting *Cratoneurion commutati* assemblages (Wołejko, 2000).

The higher concentration of nitrates can be attributed to improved water oxygenation in the aquatic environment. The analysed waters exhibited similarity in the concentration and structure of phosphorus forms (Fig. 3a).

Despite the unfavourable ratio of shoreline length to the accumulated water volume in Lake Jaczno, its trophic status is satisfactory and stable (Zieliński, Kłoczewska and Górniak, 2006; Jekatierynczuk-Rudczyk, 2013; Górniak, Więcko and Karpowicz, 2016; own research 2009 – unpublished). An important reason for the lake's low trophic level is the significant supply from spring waters, which is further evidenced by the ongoing peat-forming processes.

The variability in the concentration of biogenic elements in water was considerably higher, primarily due to the development of vegetation within natural groundwater outflows. The vegetation led to a substantially higher use of nutrients (Fig. 3c, d), especially in the growing season (Jekatierynczuk-Rudczyk, 2010; Jekatierynczuk-Rudczyk *et al.*, 2021).

The similarity in the chemical composition of groundwater, spring water, and lake water suggests hydraulic connectivity. However, the connectivity is limited in the study area due to the sediment granulometric parameters in the transitional zone. The granulometric composition influences hydrogeological parameters and water circulation rates. In Lake Jaczno, clayey sands and sandy clays exhibit low permeability, restricting free water exchange between groundwater and surface waters. Accumulated organic matter enhances sediment sorptive capacity, intensifying the process of purification. Mineral components in sediments significantly impact water quality, either enriching surface or groundwater, or eliminating specific components. During the growing season, suspended peatlands exhibit a significant lateral gradient in groundwater potential towards the lake. The presence of organic sediments facilitates the rapid migration of groundwater and surface waters in the coastal zone (Zieliński and Jekatierynczuk-Rudczyk, 2010).

The elevated organic carbon content (OCC) of more than 3% in headwater peatland and the ecotone zone of Lake Jaczno likely results from the surrounding forested areas and continuous peat-forming processes. Similar organic carbon levels were found in Lake Jaczno's bottom sediments, with $CaCO_3$ content ranging from 25 to 83%, averaging 65% (Więckowski, 2009). Headwater peatland sediments contain high nitrogen levels (Tab. 3) due to significant organic matter accumulation, serving as a potential nitrogen source for groundwater and outflows.

Despite minor variations in sediment chemical composition, distinct possibilities for the circulation of chemical compounds were observed in the ecotone at Lake Jaczno. The saturation index (SI) is often used to interpret processes occurring in spring bogs (Ziułkiewicz *et al.*, 2012). Analysis of saturation indices against minerals revealed oversaturation with iron oxides and hydroxides, iron and calcium carbonates, and calcium and iron phosphates, while being undersaturated with manganese oxides and hydroxides (Fig. 4). This suggests the potential deposition of these compounds, which is visible in streams flowing through the headwater peatland as precipitation on vegetation. A distinguishing feature of the studied aquatic habitats is the solubility of magnesium and manganese compounds, potentially leading to higher concentrations of these elements in the water.

Recent studies suggest that ecotones, known for their active biogeochemical processes, serve as pivotal monitoring points for assessing changing environmental conditions and the availability of crucial limiting factors (Eberhard, Kane and Marcarelli, 2023). Despite their significance in north-east Poland for evaluating groundwater quantity and quality, natural groundwater outflows require continuous monitoring. These outflows undergo physical and chemical changes due to weathering and denudation processes, with dissolved substances originating from various sources, including atmospheric deposition, biological activity, and human influences (Lewandowski *et al.*, 2015). The inventory and analysis of crenological features enable assessing potential natural or human-induced changes in aquifers. Natural groundwater outflows capture environmental changes from diverse human

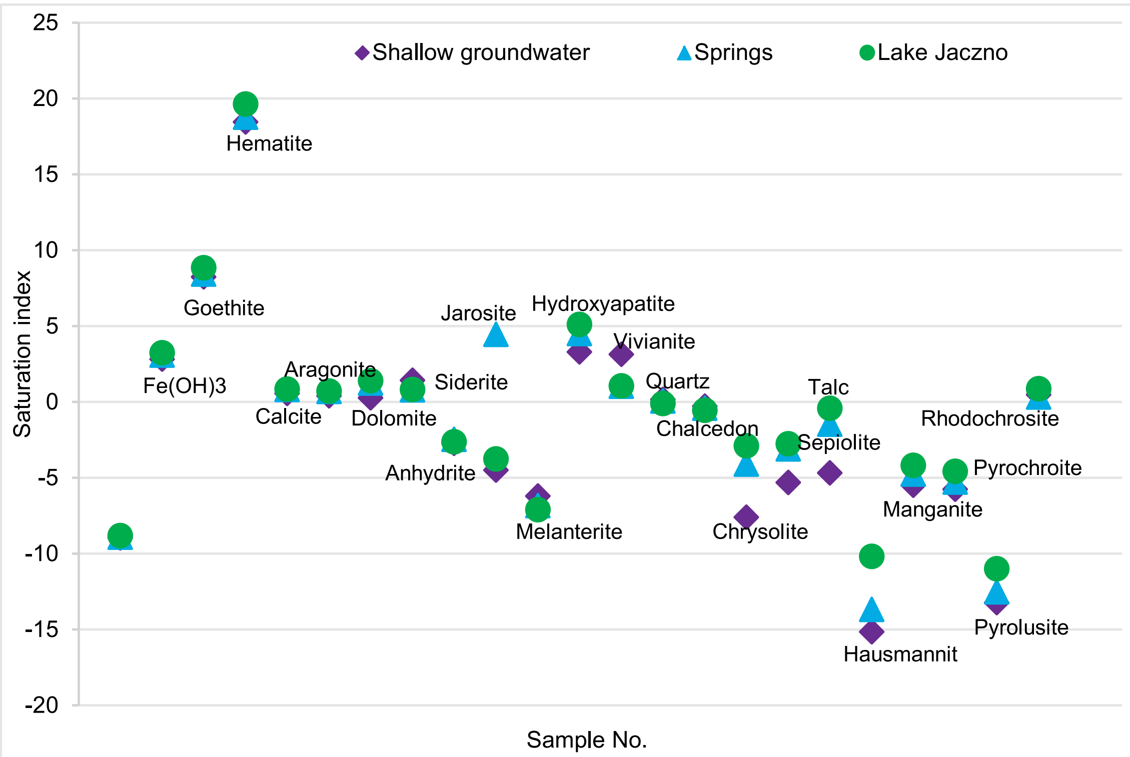

Fig. 4. Saturation index (*SI*) values concerning different mineral types in the shallow groundwater, springs and Lake Jaczno; source: own study

activities (Jekatierynczuk-Rudczyk *et al.*, 2023). While unconditional protection is mandated in national parks and reserves, the effectiveness of conditional protection in landscape parks may vary depending on local factors. The peatlands surrounding Lake Jaczno, which are located on private land, face challenges related to the establishing of nature reserves.

CONCLUSIONS

1. The hydrological stability of the analysed habitat is evident from low variability in yield during the growing season. Evaluating the hydrochemistry of headwater peatlands is challenging, as physical water parameters display low temporal variability. However, the concentration of biogenic elements exhibit higher variability, influenced by flora development in areas with natural groundwater outflows. Chemical parameters of sediments at Lake Jaczno indicate the buffering capacity of transitional zones between water and land.
2. Groundwater, spring water, and lake water in the Suwalski Landscape Park maintain high quality, with no significant changes in chemical composition over the past decades. However, despite similarities in chemical composition, sediment granulometry suggests low permeability, which may potentially restrict the exchange between groundwater and surface waters.
3. Monitoring of natural groundwater outflows, including yields and physico-chemical composition, is vital for the accurate assessment of groundwater resources and their quality.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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