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SPATIO-TEMPORAL DIFFERENCES OF SEDIMENT ACCUMULATION RATE IN THE LAKE GOŚCIĄŻ (CENTRAL POLAND) AS A RESPONSE OF METEOROLOGICAL CONDITIONS AND LAKE BASIN MORPHOMETRY

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ABSTRACT. Weather conditions and lake basin morphometry are of key importance in the study of sediment accumulation rate in lakes. This study aims to determine how these factors affect spatial and seasonal variations in sedimentation rate in the epilimnion and hypolimnion of Lake Gościąż. To determine sedimentation rates, six sedimentation traps were set up at different locations and depths in the lake. Weather data were obtained from a meteorological station near the lake. Furthermore, temperature in the lake water column was measured continuously, and during field work oxygenation and transparency were also measured. Seasonal changes in sediment composition were analyzed on smear slides under microscope. The study showed that sedimentation rate increased as bottom steepness increased, and that there was more sediment in the hypolimnion than the epilimnion, especially in spring and autumn. There was a clear seasonal variation in early-spring and autumn peaks in sedimentation. The obtained results were significantly dependent on bottom relief, wind and air temperature through these factors' influence on water temperature. The results show that the sediment accumulation rate in Lake Gościąż depends on the hydrodynamic conditions, which are determined by wind speed, wind direction, water temperature, and the shape and steepness of the lake basin. The relief features of the lake bottom and its orientation relative to the prevailing wind are significant factors in the spatial differentiation in sediment accumulation rate and composition of sedimenting material. It has been shown that the lake's shallow-water zone (littoral and sublittoral) is an important source of the material accumulated in the profundal zone. The patterns and mechanisms of the course of contemporary sedimentation in Lake Gościąż, as determined based on the conducted investigations, can be applied in the study of other lakes and in assessing the representativeness of sampling sites for laminated bottom sediments to be used in palaeo-environmental studies.

Diferencias espacio temporales de la tasa de acumulación de sedimentos en el lago Gościąż (Polonia central) como respuesta a las condiciones meteorológicas y a la morfometría del lago

RESUMEN. Las condiciones meteorológicas y la morfometría de la cuenca son clave en el estudio de las tasas de sedimentación en lagos. Este trabajo tiene como objetivo analizar cómo estos factores afectan a las variaciones espaciales y estacionales de la tasa de sedimentación en el epilimnion y el hipolimnion del lago Gościąż. Para determinar las tasas de sedimentación, se instalaron seis trampas de sedimentos en diferentes localizaciones dentro del lago y a diferentes profundidades. Los datos meteorológicos se obtuvieron de una estación próxima al lago. Además, se midió de manera constante la temperatura de la columna de agua y, durante campañas de campo, su grado de oxigenación y transparencia. Se analizaron cambios estacionales en la composición del sedimento mediante frotis para microscopio. El estudio indica que la tasa de sedimentación incrementó conforme la pendiente del fondo del lago aumentaba, y que había más sedimento en el hipolimnion que en el epilimnion, especialmente en verano y en otoño. Se observó una clara variación estacional en los picos de sedimentación al principio de la primavera y en otoño. Los resultados dependieron significativamente del relieve del fondo del lago, del viento y de la temperatura del aire, que a su vez influenciaron la temperatura del agua. Los resultados muestran que la acumulación de sedimento en el Lago Gościąż depende de las condiciones hidrodinámicas, las cuales están determinadas por la velocidad y dirección del viento, la temperatura del agua y la pendiente del fondo del lago. Las características del relieve del fondo del lago y su orientación relativa a los vientos predominantes son factores significativos que explican la diferenciación espacial de la tasa de sedimentación y la composición del material sedimentado. Las zonas someras del lago (litorales y sublitorales) son una fuente importante de sedimento del material acumulado en la zona profunda. Los patrones y mecanismos de la sedimentación contemporánea del lago Gościąż, definidos en este trabajo pueden ser aplicados al estudio de otros lagos, así como en la evaluación de la representatividad de sitios de muestreo para sedimentos laminados en estudios paleoambientales.

Key words: Lake morphometry, dimictic lake, sediment resuspension, sediment accumulation rate, hydrometeorological monitoring.

Palabras clave: Morfometría lacustre, lago dimíctico, resuspensión de sedimentos, tasa de acumulación de sedimento, seguimiento hidrometeorológico.

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1. Introduction

Lake sediments are excellent archives of changes taking place in the natural environment, because lakes react very quickly to changes in their surroundings (Vos *et al*., 1997). Of particular usefulness in this regard are annually laminated sediments, i.e. varves, which show regional and local changes at high-resolution (Segerstrom *et al.*, 1984; Goslar, 1993; Leeman and Niessen, 1994; Schaller *et al.*, 1997; Moore *et al.*, 2001; Schettler *et al.*, 2006; Ojala *et al.*, 2008; Kaal *et al.*, 2015; Zolitschka *et al.*, 2015; Bonk *et al.*, 2016; Ott *et al.*, 2017) but are relatively rare (Tylmann, 2011; Ojala *et al.*, 2012; Zolitschka *et al.*, 2015). Anaerobic conditions at the lake bottom are required for the preservation of varves, as confirmed by the fact that they coincide spatially with bottom areas covered by the hypolimnion in dimictic lakes or the monimolimnion in meromictic lakes (Petterson *et al.*, 1993; Tylmann *et al.*, 2012; Salminen *et al.*, 2019). Therefore, the potential drivers of annual lamination discontinuity or its absence are syn- and metasedimentary disturbances to the sediment (O'Sullivan, 1983) caused by dwelling organisms, strong winds leading to intense water column mixing or a deep-lying thermocline (Horppila and Niemistö, 2008).

In order to fully exploit the information on environmental changes preserved in laminated sediments, and thus to create a reliable and accurate chronology, it is necessary to understand the mechanisms affecting the formation of these sediments (Lotter and Birks, 1997; Bonk *et al.*, 2015). For this, monitoring of contemporary lake sediments, which reflect current seasonal changes, is an excellent tool. Observing changes requires sediment traps, as well as monitoring of the meteorological and hydrological conditions in the catchment (Leeman and Niessen, 1994; Ojala *et al.*, 2014). Sediment traps are a fairly common limnological research method but in the study of annually laminated lake sediments, their popularity is relatively recent, and is still growing (Flower, 1990; Mieszczankin, 1997; Bluszcz *et al.*, 2008; Bonk *et al.*, 2015; Kienel *et al.*, 2017; Maier *et al.*, 2018; Johansson *et al.*, 2019). The results of this type of research are difficult to integrate with morphometric and meteorological conditions, and hence it is relatively rarely done. The basic research involves capturing suspended matter (also known as "seston" [Ruttner, 1963]) in the lake's water; this is a component of the lake's primary production and a supply of allochthonous material (Wetzel *et al.*, 1972; Gasith, 1976). Primary production can affect the amount of sediment directly by biological particles, and indirectly through calcium carbonate precipitating in biogeochemical processes (Groleau *et al.*, 2000). The biological production volume in the lake is affected most strongly by nutrient supply (Pace and Lovett, 2013). Meteorological impacts are usually taken into consideration less frequently in studies of lake productivity, although they are becoming more important as climate conditions change dynamically and human impact increases. Factors related to meteorological conditions may also affect the redistribution of plankton within the lake and sediment resuspension, especially in very shallow parts (Dearing, 1997). The spatial diversity of sedimentation is also influenced by lake basin morphology, i.e. the steepness of the lake basin slopes and the number and arrangement of the basins composing the water body (Punning *et al.*, 2004).

Lake Gościąż is widely known for its annually laminated lake sediments, which occur throughout almost the entire sediment profile of the deepest part of the lake (Ralska-Jasiewiczowa *et al.*, 1998). Only recently, a detailed investigation of varve microfacies combined with multiproxy dating techniques have allowed a new chronology to be developed for the Lake Gościąż sediment record, establishing the onset of lacustrine sedimentation in the late Allerød at 12,844 +213/-311 varve yrs BP (Bonk *et al.*, 2021; Müller *et al.*, in press). Studies of contemporary sedimentation using sediment traps were first used in Lake Gościąż in 1988. Further studies were performed in 1991 (Kentzer and Żytkowicz, 1993) and in 1993-95 (Mieszczankin, 1997). They were conducted to analyse sediment composition (content of N, P, $CaCO_3$, organic matter and plant pollen), differentiation of sedimentation rate in the water column, and seasonal variability of sedimentation rate (Kentzer and Żytkowicz, 1993; Mieszczankin and Noryśkiewicz, 2000). Research conducted in the 1990s showed that the sedimentation rate in Lake Gościąż is as much as several times higher than in other lakes with annually laminated sediments, and these differences result from its higher trophy and large contribution of resuspended matter (Mieszczankin, 1997). These studies were conducted using material collected from sediment traps located along a north-south axis. Our research analysed the course of sedimentation in an east-west transect, along the lake's longer axis and the prevailing wind direction. Thus, only the results of the analysis of the sedimentation rate at the site in the deepest part of the lake will be comparable.

The main objective of the presented research is to recognise the determinants of the course of contemporary sedimentation and the qualitative composition of sedimenting material. This study therefore aims to show the impact of meteorological factors and basin topography on the spatial differentiation of the sediment accumulation rate in the lake's epilimnion and hypolimnion. This issue will be presented against the seasonal variability in deposited matter. To achieve this goal, complementary meteorological and hydrological monitoring, which has not been conducted in the Lake Gościąż catchment area before, was carried out.

2. Material and methods

2.1. Study area

Lake Gościąż is located in the Gostynin Lakeland (Central Poland) at an elevation of 64.3 m a.s.l. (Fig. 1). The lake is located in a widening in the valley of the lower (lowland) course of the Vistula River (the longest river in Poland). This area was initially formed under the influence of glacial erosion and, later, fluvioglacial and fluvial erosion. The coexistence of accumulation and erosion processes led to the deposition of a series of sandy–gravelly sediments with an average thickness of 40-45 m (Skompski, 1969). The area's relief was shaped during the Weichselian glaciation and the

Holocene. Its essential features are subglacial channels and fluvioglacial terraces (Wiśniewski, 1976). Sandy dunes created by aeolian activity in the Late Glacial are also abundant in this area (Urbaniak, 1967; Rychel *et al*., 2018; Kruczkowska *et al.*, 2020). Lake Gościąż lies at the bottom part of a subglacial channel that developed during the recession of the Last Glacial ice sheet around 18,000 years ago. The lake formation started during the transition from Bølling to Allerød as a result of dead ice melting (Ralska-Jasiewiczowa *et al.*, 1998). The properties of the relief and geological structure allow the Vistula's valley and bed to maintain hydrogeological connections to their adjacent areas. In such conditions, subglacial channels whose course runs vertically relative to the direction of groundwater flow are fed by groundwaters of local and regional circulation system (Gierszewski, 2000). In combination with other environmental features (including the poorly-varied subsoil lithology, high afforestation, and low human impact on the environment), this ensures that Lake Gościąż receives a steady supply of groundwater of relatively stable chemical composition, which in turn also results in a steady amount of sedimentation and stable sediment characteristics.

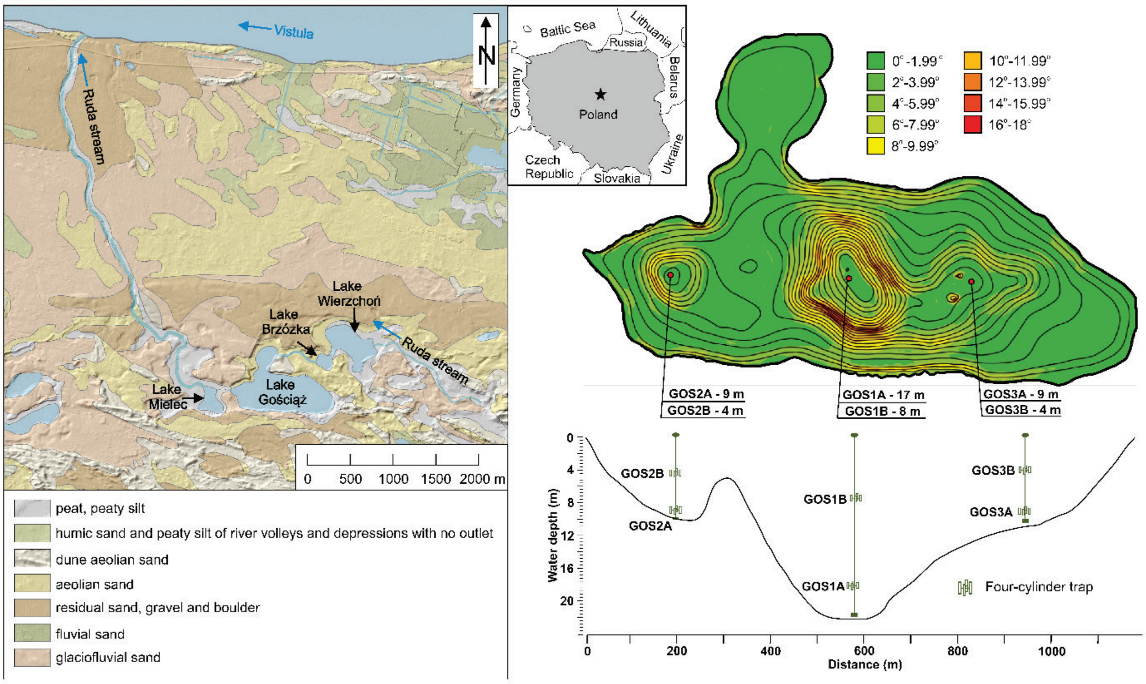


Figure 1. Location of the study area and the bathymetry and slope steepness map of Lake Gościąż with marked locations of sediment traps (geological background of the Lake Gościąż catchment area on the basis of Rychel et al.*, 2014).*

The climate in this area is classified as cold temperate with warm summers (Peel *et al.*, 2007). According to data from 1967-2015, the annual average temperature is 8.2°C, while the average sum of precipitation is 533 mm (Bartczak *et al.*, 2019). The growing period lasts 210-215 days (Demidowicz *et al.*, 1998). Westerly winds prevail in this area (Woś, 1999).

The lake catchment area is covered with pine forests. There are communities of *Querco roboris-Pinetum* wetter habitats, and *Peucedano-Pinetum* in drier locations (Kępczyński and Noryśkiewicz, 1998). There is a community of *Carici elongatae-Alnetum sensu lato* immediately around the lake, and a *Tilio-Carpinetum* community slightly further away. On submerged shores there are also brushwood communities represented by *Salicetum pentandro-cinereaes*. Aquatic vegetation inhabits the shallowest parts of the lake, especially in the shallow bay to the north. This vegetation is represented mainly by communities of *Lemno-Spirodeletum polyrrhizae, Hydrocharitetum morsus-ranae, Elodeetum Canadensis* and *Potamogetonetum pectinati,* and less commonly by *Potamogetonetum filiformis*, and also, at the south-western shore of the lake, by *Potamogetonetum perfoliati*. The slightly silty littoral parts of Gościąż Lake are overgrown with reedswamps. The largest areas are occupied by *Phragmitetum communis* and *Typhetum angustifoliae*. Smaller areas are occupied by *Glycerietum maximae, Eleocharitetum palustris* and *Acoretum calami* (Kępczyński and Noryśkiewicz, 1993).

Lake Gościąż is small (0.417 km^2) and relatively deep (maximum depth 22.1 m) (Table 1). It consists of two basins: a shallow northern one (Tobyłka Bay) and a main one with two clearly distinguished sub-basins. The lake is deepest in the middle (Fig. 1). Along with three other lakes – Mielec, Brzózka and Wierzchoń – Lake Gościąż forms a lake system called “Na Jazach”, which is connected by the stream Ruda. In the middle course of the stream, below Lake Gościąż, there is a weir that has existed in its present form since 1989 and is a remnant of a mill built in the 16th century. The groundwater watershed of the catchment area is 56 km^2, of which 39 km^2 is endorheic (Glazik, 1978; Gierszewski, 2000). The lakes in the studied catchment area are fed primarily (ca. 90%) by groundwater, mainly from the south (Gierszewski, 2000). The groundwater supplying the Lake Gościąż is of Ca-HCO_3-SO_4 type, with low mineralisation (averaging 260 $mg \cdot dm^{-3}$) (Gierszewski,, 2000; 2001). The biogeochemical changes in the lake have a slight effect – a decrease of 20 $mg \cdot dm^{-3}$ in the total mineralisation of the water, mainly seen in lower concentrations of Ca and SO_4 ions. As a result, the ionic type of the water also changes to Ca-Mg-HCO_3. The supply of nutrients in the groundwater exceeds safe thresholds for the harmonious functioning of the lake. In the years 1991–93 this averaged about 3g P m^{-2} and about 40 g N m^{-2}. The N:P ratio of 14:1 indicates that in terms of fertility, Lake Gościąż is eutrophic (Giziński *et al.*, 1998).

Table 1. Morphometric parameters of the Lake Gościąż.

Location	**52°34’58’’N 19°20’23’’E**
Water level (m a.s.l.)	64.3
Surface (km^2)	0.417
Maximum length (m)	1180
Maximum width (m)	723
Medium width (m)	357
Maximum depth (m)	22.1
Average depth (m)	5
Elongation indicator (m)	1.59
Shoreline length (m)	3452
Development of the coastline	1.51
Capacity (m^3)	2 073 000

The lake freezing period averages about 75 days in this region (Choiński *et al.*, 2015). In terms of mixing, Lake Gościąż represents a bradimictic type (Churski and Marszelewski, 1998). The lake has a well-developed summer stratification, with a distinct thermocline with a strong gradient of 3.5 $^{o}C\ m^{-1}$. At the same time, the level of oxygenation diminishes steadily down though the water column (Gierszewski, 2000). The deoxygenated waters of the hypolimnion have a higher concentration of Ca^{2+} (25%), HCO_3^{2-}, NH_4^+ and PO_4^{3-} ions. However, the concentration of SO_4 (20%) and the pH of the water are significantly lower. The chemical properties of the water in Lake Gościąż (in addition to the assimilation of biogenic substances by aquatic organisms) is transformed by changes related to the functioning of the carbonate system and redox reactions (Gierszewski, 2000).

Due to its morphological and hydrobiological features, Lake Gościąż has two zones with different water dynamics: a shallow-water zone (to a depth of 5-6 m), which covers about 50% of the lake's bottom surface, and a deep-water zone. The bottom sediments in the polymictic shallow-water zone are subject to frequent redeposition and displacement towards the middle of the lake. The highest accumulation of sediments occurs in the deep-water zone, which is static and deoxygenated during the summer stratification (Giziński *et al.*, 1998). The studies conducted in the 1990s showed the mean sedimentation rate to be 5.9 g $m^{-2}d^{-1}$ in the epilimnion and 13.1 g $m^{-2}d^{-1}$ in the hypolimnion (Mieszczankin, 1997). The maxima occurred during overturn, and the minima in summer stratification periods. The low summer sedimentation rate is conditioned by the thermocline, which is a natural barrier to the sedimentation of matter. The greater sedimentation in traps in the hypolimnion, especially during overturns, is associated with resedimentation processes, and during summer stratifications should be connected with the "funnel effect". The most important component of sediment was $CaCO_3$ (Giziński *et al.*, 1998).

2.2 Sampling and analyses

Sediment samples were collected from August 2017 till May 2019 at four- to seven-week intervals except for periods of ice cover on the lake. The research was carried out using sediment traps at three different points in the lake (GOS 1, GOS 2 and GOS 3) (Fig. 1). At each, two sediment traps were installed: one in the lower epilimnion (traps GOS 1B, 2B and 3B) and the other in hypolimnion above the bottom (traps GOS 1A, 2A and 3A). Each trap consisted of four cylinders of 8 cm in diameter and 50 cm high. In the deepest part of the lake (GOS 1) thermal monitoring was also conducted using a HOBO Water Temperature Pro v2 Data Logger. The water temperature was measured at 30-minute resolution at depths of 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 18 and 20 m. During each sediment traps receiving, a Secchi disc was also used to measure water transparency, and in the period from July 2017 to December 2018, a Hanna HI 9829 multiparametric meter was also used to measure the dissolved oxygen content at the lake's deepest point (GOS 1), from the surface down to the bottom. In 2017, bathymetric measurements of the lake were taken with a Lowrance HDS-7 echosounder.

The course of weather conditions was recorded using a HOBO RX300 Station - CELL-3G automatic weather station at 2 km from the lake. The station records the following parameters hourly: air temperature, precipitation, and direction, speed and gusts of wind. Lake water levels were recorded every 0.5 h using a HOBO U20-001-04 water level recorder.

To determine dry weight of sediment, the material from sediment traps was centrifuged and dried for 24 h at 105°C, and then weighted to an accuracy of 0.001 g. Mean sediment-accumulation rate was expressed in grams of dry matter per square metre per day (g m^{-2} d^{-1}).

To determine the quantitative composition, sediment samples were analysed for the content of organic matter, calcium carbonate, and biogenic and terrigenous silica. Organic matter content was determined by roasting of the sample for 4 hours at 550°C (Heiri *et al.*, 2001), and calcium carbonate by the Scheibler method. Biogenic silica concentration was calculated as the difference in weight between total silica content and the share of terrigenous silica. Total silica was determined after dissolution of acid-soluble fractions and organic matter in H_2SO_4, and the terrigenous silica was the residue after removal of opaline (biogenic) silica from the total silica with 0.5n NaOH in a water bath at 100°C for 2 hours (Bechtel *et al.*, 2007). The difference between 100% and the total sum of organic matter, $CaCO_3$, terrigenous and biogenic silica represents "mineral residue" (MR). The "mineral residue" includes hot-acid-extractable compounds excluding carbonates (e.g. sulphides, some clay minerals, etc.) (Woszczyk *et al.*, 2009).

Prior to smear slide preparation, 66 fresh sediment trap samples were transferred to a microscope slide and dried on a heating plate. Then, a cover slip was placed on the dried sediment using glycerine. Ready smear slides were analysed under a light microscope at 20× to 200× magnification to track the seasonal changes within the sediment components. This analysis is only a semi-quantitative analytical tool, but it provides insights into the sediment components and allows to recognize a relative change in lithology (Schnurrenberger *et al.*, 2003). The components of material retrieved from sediment traps can be grouped in three categories: organic, diatoms and carbonates.

The twenty-month-long measurement period of water temperature made it possible to construct depth profiles of water temperature (Surfer Software) for the deepest part of the lake (GOS 1). The data from bathymetric measurements were next converted into numerical .csv files, which were processed by Arc GIS version 10.2.2 software (ESRI 2014) to generate a bathymetric map and a map of bottom slope steepness. The bathymetric data were used to calculate the morphometric parameters of the lake basin.

3 Results

3.1 Sediment accumulation rate

Mean sediment accumulation rate in each of the three monitored locations was higher in the traps in the hypolimnion (deeper trap). In the epilimnion traps, the accumulation varied from 0.94 g m^{-2} d^{-1} to 5.95 g m^{-2} d^{-1} (Fig. 2). The lowest sediment accumulation rate for traps GOS 1B and GOS 3B were measured in winter 2018-19 and reached only 1.24 g m^{-2} d^{-1} and 1.18 g m^{-2} d^{-1}, respectively. In trap GOS 2B, the accumulation rate was lowest between 27 July and 25 August 2017, and amounted to 0.94 g m^{-2} d^{-1}. The largest amount of sediment was accumulated in trap GOS 1B between 13 July and 13 August 2018 (4.24 g m^{-2} d^{-1}), in GOS 2B between 26 August and 9 October 2017 (5.95 g m^{-2} d^{-1}), and in GOS 3B between 14 March and 11 April 2019 (4.54 g m^{-2} d^{-1}). In the traps located in the hypolimnion, the sediment accumulation rate varied from 1.93 g m^{-2} d^{-1} to 10.21 g m^{-2} d^{-1}. The lowest accumulation rate in GOS 1A was measured between 25 May and 12 July 2018 (1.93 g m^{-2} d^{-1}), whereas in traps GOS 2A and GOS 3A, it was between 5 December 2018 and 13 March 2019 (2.17 g m^{-2} d^{-1} and 1.46 g m^{-2} d^{-1}, respectively). In GOS 1A, the sediment accumulation rate was highest between 10 October and 10 November 2017, and reached 10.21 g m^{-2} d^{-1}. In GOS 2A and GOS 3A it was the highest from 14 March till 11 April 2019, amounting up to 8.28 g m^{-2} d^{-1} and 6.47 g m^{-2} d^{-1}, respectively. There is no data on the course of sedimentation in the GOS 1A and GOS 2B traps from October 2018 to April 2019 and in the GOS 3A trap from May 2018 to October 2018 because the traps disappeared. It should also be noted that the results obtained for April 2018 (containing sedimentation material from the winter season) are a value averaged over the five-month period. Therefore, these samples contain material from the end of the autumn overturn, the winter and early spring. Mean sediment accumulation rate in the deepest location (GOS 1) was 71% higher in the hypolimnion than in the epilimnion. In the western location (GOS 2), the difference reached 57% in favour of the deeper trap, while in the eastern part of the lake (GOS 3) it was only 29%. In the deepest lake sub-basin (near GOS 1), slope steepness on the south-western side is up to 18º (Fig. 1). In the western part (near GOS 2), it is up to 14º, while in the eastern part (near GOS 3), where sedimentation values are the lowest, slope steepness does not exceed 4º. In the hypolimnion, the trap in the western part (GOS 2A) accumulated on average 41% more sediment than the one in the eastern part (GOS 3A), while in the deepest part of the lake (GOS 1A) the western trap averaged 38% more than the eastern trap (GOS 3A). In the traps in the epilimnion, the average sediment accumulation rate was 16% higher in the western part of the lake (GOS 2B) than in the eastern part (GOS 3B), and in the deepest part (GOS 1B) it was 5% higher than in the east (GOS 3B).

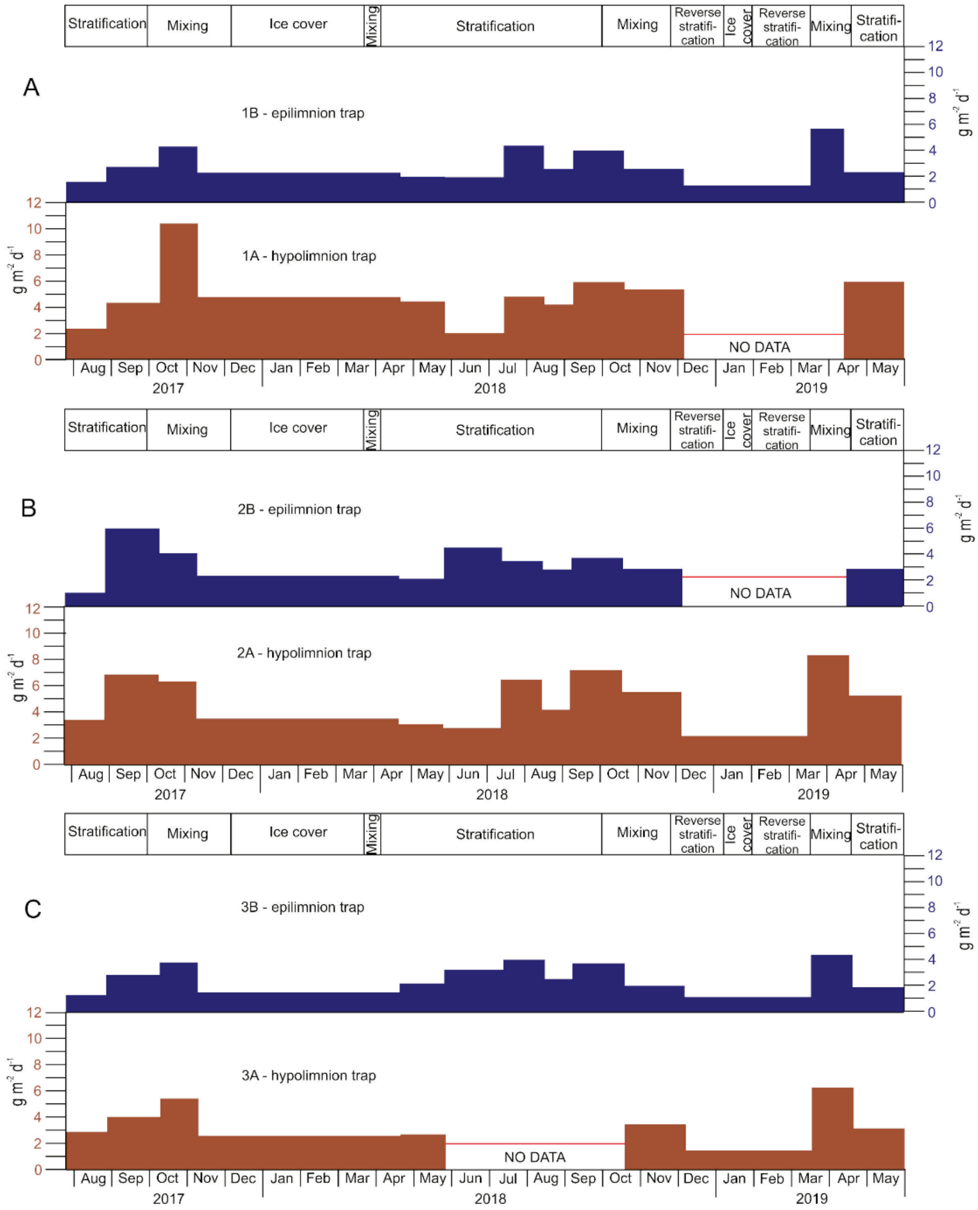
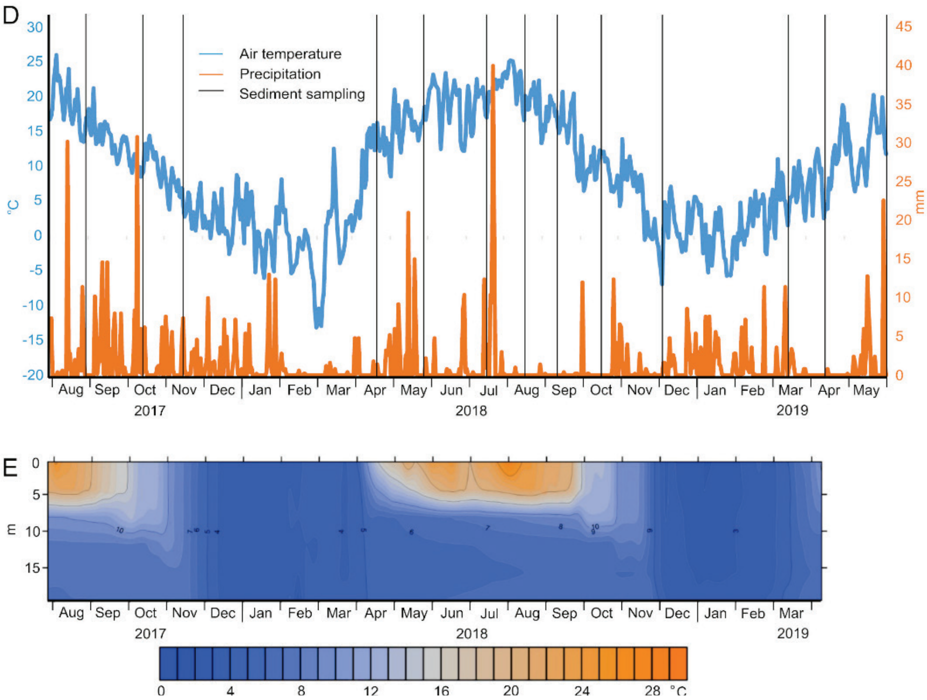


Figure 2. Sediment accumulation rate in Lake Gościąż: A - sediment traps GOS1A and 1B; B - sediment traps GOS2A and 2B; C - sediments traps GOS3A and 3B. No data 1A (December 2018 - April 2019), 2A (December 2018 - April 2019), 3B (May 2018 - October 2018); D - air temperature (blue line), precipitation (orange line) and time of the sediment trap retrieving (black bars); E - variability in thermal conditions at the deepest site in Lake Gościąż.



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3.2 Meteorological conditions

The highest air temperature in the study period was 35.3°C, recorded on 9 August 2018, whereas the lowest value was -19.6°C, recorded on 27 February 2018. Mean daily temperatures (Fig. 2D) varied from 26.0°C (1 August 2017) to -13.1°C (26 February 2018). The highest monthly precipitation of 103.4 mm was observed in July 2018, compared to only 1 mm in April 2019. Daily precipitation was the highest on 18 July 2018 (40 mm).

The prevailing winds were southerly (26.9%), south-westerly (21.9%), northerly (18.2%), and north-westerly (15.6%). In autumn and winter, we detected markedly higher contributions of southerly winds (157.5°-202.5°), with up to 51.6% in October 2017, and south-westerly winds (202.5°-247.5°), with up to 36.9% in December 2018. In spring and summer of each year, winds were mostly northerly (337.5°-22.5°), north-westerly (292.5°-337.5°), and westerly (247.5°-292.5°) (Fig. 3). Generally, during the studied seasons, winds along the NE-SW axis dominated from September till April. Particularly conspicuous was the dominance of winds from the directions 180°-270°, which in October-November 2017 reached as much as 85% of the total. In the summer half-year (April-October), the dominant wind directions were 270°-360°, as their percentage contributions were then around 70%, with up to 78% in May-July 2018. The average wind speeds in individual measurement series ranged from 0.58 m s^{-1} (Aug-Sept 2018) to 0.85 m s^{-1} (Mar-Apr 2019) (Table 2). However, in terms of their impact on the lake-water hydrodynamics, momentary wind speeds – gust speeds – are important. Longer periods of wind with higher gust speeds were found in October 2017, March, June, July and October 2018, and March 2019. The maximum wind speed values measured ranged from 6 to 13.1 m s^{-1}.

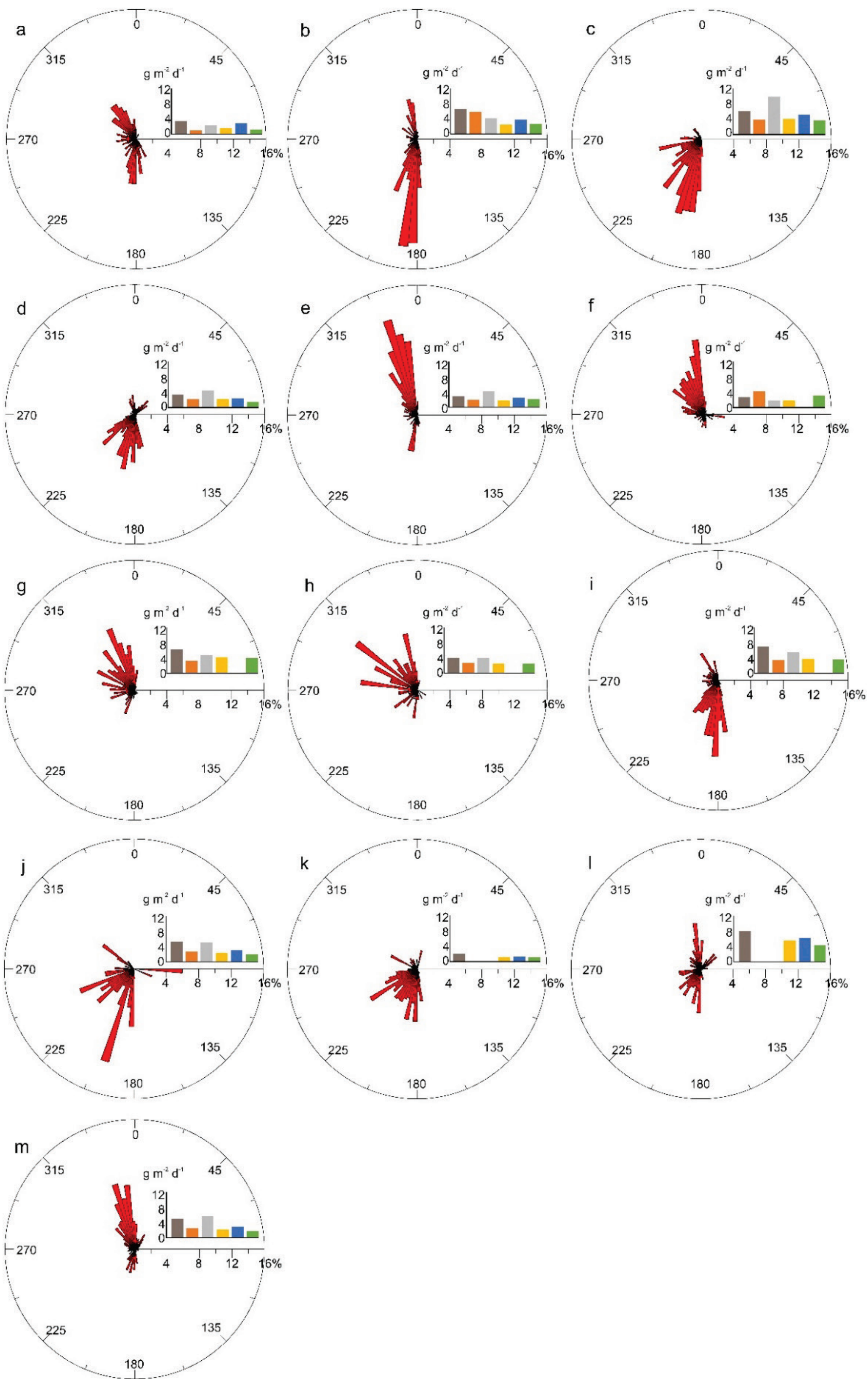

Figure 3. Wind direction: a – 27 July 2017- 25 Aug 2017; b – 25 Aug 2017 - 9 Oct 2017; c – 9 Oct 2017-10 Nov 2017; d – 10 Nov 2017-19 Apr 2018; e – 19 Apr 2018-25 May 2018; f – 25 May 2018-12 Jul 2018; g – 12 Jul 2018-13 Aug 2018; h – 13 Aug 2018-7 Sep 2018; i – 7 Sep 2018-15 Oct 2018; j – 15 Oct 2018-4 Dec 2018; k – 4 Dec 2018-13 Mar 2019; l – 13 Mar 2019-11 Apr 2019; m – 11 Apr 2019-30 May 2019; Sediment traps: brown – GOS 1A, orange – GOS 1B, gray – GOS 2A, yellow – GOS 2B, blue – GOS 3A, green – GOS 3B.

Period	Sediment accumulation rate (g m^{-2} d^{-1})						Average air temp. (°C)	Precipitation (mm)	Average water temp. (°C)	Secchi Disc visibility (m)	Average speed of wind (m s^{-1})
	GOS 1A	GOS 1B	GOS 2A	GOS 2B	GOS 3A	GOS 3B					
27 Jul 2017 – 25 Aug 2017	2.299	1.531	3.410	0.939	2.831	1.245	18.86	73.4	23.28	2.15	0.63
25 Aug 2017 – 9 Oct 2017	4.255	2.623	6.786	5.954	4.001	2.759	13.30	136.6	16.88	1.80	0.65
9 Oct 2017 – 10 Nov 2017	10.209	4.209	6.321	4.002	5.417	3.829	9.26	42.0	11.00	1.80	0.78
10 Nov 2017 – 19 Apr 2018	4.623	2.270	3.481	2.233	2.492	1.549	1.89	152.8	5.02	1.90	0.84
19 Apr 2018 – 24 May 2018	4.321	1.902	3.044	2.047	2.585	2.180	15.44	80.0	18.98	5.00	0.72
24 May 2018 – 12 Jul 2018	1.933	1.899	2.741	4.471		3.244	19.02	45.8	22.75	2.00	0.76
12 Jul 2018 – 13 Aug 2018	4.828	4.242	6.382	3.300		4.159	21.80	90.6	25.44	1.25	0.60
13 Aug 2018 – 7 Sep 2018	4.069	2.514	4.182	2.725		2.624	18.38	1.6	22.90	1.40	0.58
7 Sep 2018 – 15 Oct 2018	5.836	3.930	7.216	3.652		3.879	12.73	13.4	16.94	1.95	0.73
15 Oct 2018 – 4 Dec 2018	5.250	2.501	5.410	2.747	3.235	2.043	5.36	45.2	8.59	2.90	0.88
4 Dec 2018 – 13 Mar 2019		1.244	2.169		1.460	1.178	1.68	149.6	3.02	1.00	0.82
13 Mar 2019 – 11 Apr 2019		5.722	8.283		6.474	4.540	7.12	10.6	7.63	1.45	0.85
11 Apr 2019 – 30 May 2019	5.798	2.263	5.159	2.837	3.087	1.967	12.38	72.8		3.50	0.75

Table 2. Sediment accumulation rate, weather and limnological conditions.

3.3 Limnological conditions

The amplitude of water level fluctuations in Lake Gościąż in the period from July 2017 to May 2019 was 40 cm. In the first (incomplete) monitoring season (from July 2017), a thermal stratification was developed until the end of September 2017 (Fig. 2E). At the beginning of October 2017, the autumn mixing began. The water column mixed fully in the second half of November 2017. At the beginning of December 2017 an ice cover appeared on the lake and lasted until mid-March 2018. During this time, reverse stratification was observed. After the ice cover melted, the spring mixing took place. The first days of May 2018 showed the beginning of stratification, which progress was briefly interrupted by a cooling mid-month when the air temperature during the day did not exceed 20°C. In the second half of June 2018, the water temperature in the epilimnion fell again, caused by the onset of a sharp chill. Within an hour, the air temperature dropped dramatically by 15°C, and did not exceed 16°C for next several days. In the first decade of July 2018, the temperature of the surface layer rose again and remained stable until the second half of September 2018. During the thermal stratification of the lake, the hypolimnion was completely anoxic, as recorded in measurements of oxygen concentration in the water (Fig. 4A). In May 2018, a total oxygen deficit was found from a depth of 10 m downwards, and from 8 m in June 2018. At the beginning of August 2018, oxygen conditions in the hypolimnion improved slightly. In October 2018, the autumn mixing began, and was completed in the beginning of December 2018. Ice cover appeared on the lake in the second half of January 2019 and lasted for only about a month. Reverse stratification then developed. After the lake had thawed, there was a spring mixing. The thermal stratification phase of the lake began in the first half of April 2019 already. The water measurements revealed substantial variations in temperature (up to 3.1°C) in a short time (30 min) during the stratification period at the depth thermocline (8 m) (Fig. 4B).

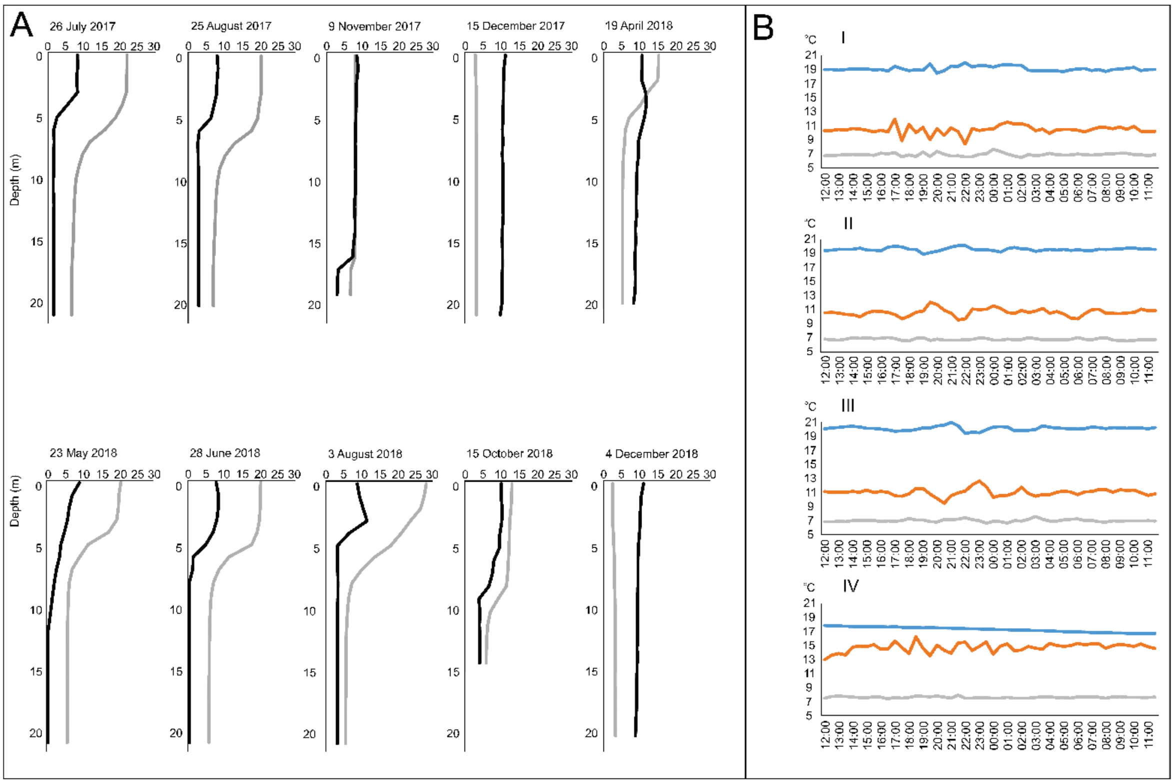

Figure 4. A: The water temperature in °C (gray line) and dissolved oxygen in mg dm^{-3} (black line) in Lake Gościąż; B: selected examples of water temperature at 6 m (blue line), 8 m (orange line), 10 m (gray line) depth. I - 18.07.2018 (12:00) - 19.07.2018 (12:00); II - 25.07.2018 (12:00) - 26.07.2018 (12:00); III - 3.08.2018 (12:00) - 4.08.2018 (12:00); IV - 24.09.2018 (12:00) - 25.09.2018 (12:00).

Measurements of Secchi disc visibility determined that water transparency was lowest (about 1 m) in early spring (March 2018 and April 2019). A noticeable increase in Secchi disc visibility was recorded in May (from 3.5 m to 5.0 m). In summer and early autumn, the water transparency again decreased to 1.0-1.5 m. After this period, Secchi disc visibility increased to 3 m.

3.4 Sedimentation cycle

The qualitative analysis of 66 smear slides showed a clear seasonal variation in sample composition. In general, sample content in a given season was similar at all locations and both depths. The annual cycle started in spring, immediately after ice cover disappearance (Fig. 5). The spring sedimentation was dominated by phytoplankton appearance (diatoms) and followed by calcite (ca. 6-8 µm) autochthonous precipitation. We also observed coarse (>6-8 µm) but rare calcite agglomerates, which in contrary to fresh, single grains, could have been transported to the lake bottom through resuspension from the littoral zone. During summer, the amount of diatoms was very low in comparison to the number of zooplankton remains, which increased markedly. Fresh calcite grains were abundant. During the autumn, sediment was enriched with fresh calcite and its agglomerates and diatoms. However, the amount of diatoms was much lower than during the spring, which leads to a conclusion that the calcite was the main component of the retrieved sediment. Deposition of mineral matter (rare grains of quartz), scarce diatoms, fungi and remains of plant tissues prevailed in the winter. During the whole cycle, a green alga (*Phacotus*) with a calcite lorica was observed.

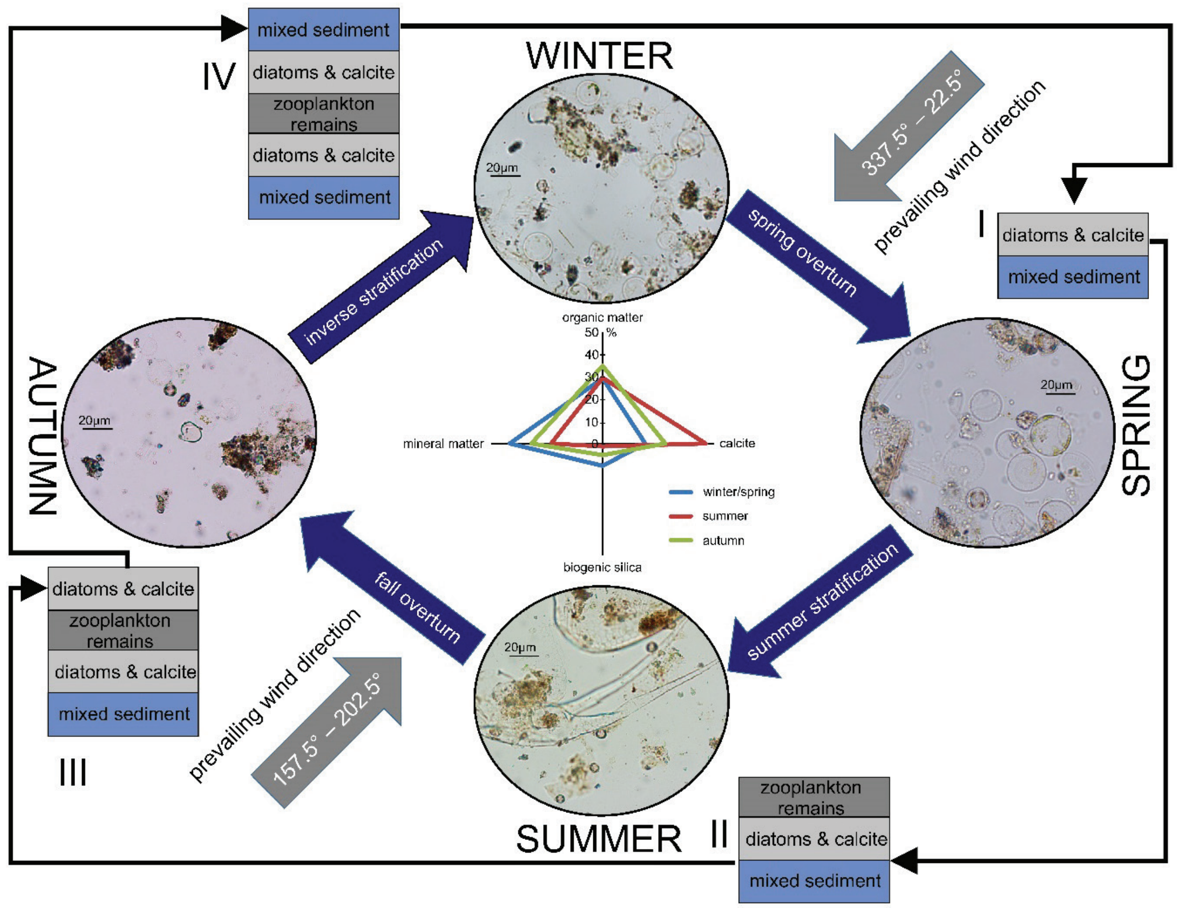

Figure 5. The seasonal changes within sedimentation cycle within Lake Gościąż.

The smear slide analysis results are generally consistent with the results of the quantitative geochemical studies on the 57 sediment samples (Fig. 6). They showed that the tested sediments comprise 18.7-53.3% of organic matter (averaging 30.9%) and 9.7-64.8% of calcium carbonate (averaging 28.7%). The highest contribution of organic material was found in samples representing the summer and autumn months. Calcium carbonate sedimented mainly in summer (July, August). The lowest content of calcium carbonate was measured in samples taken in spring (April, May). Biogenic silica accounted for 0.4-27.3% (averaging 6.2%) and terrigenous silica for 0.8-41% (averaging 14.5%). Both forms of silica were most strongly represented in spring and autumn samples. The seasonal variability of the sediment composition was, however, very similar across all locations for particular measurement series. Against this background, however, the GOS 3A site stands out, as its sediments had a significantly higher content of terrigenous material and a lower content of calcium carbonate. The GOS 2 site was also particular, as, unlike the other two, it had a clearly greater vertical differentiation in biogenic silica content.

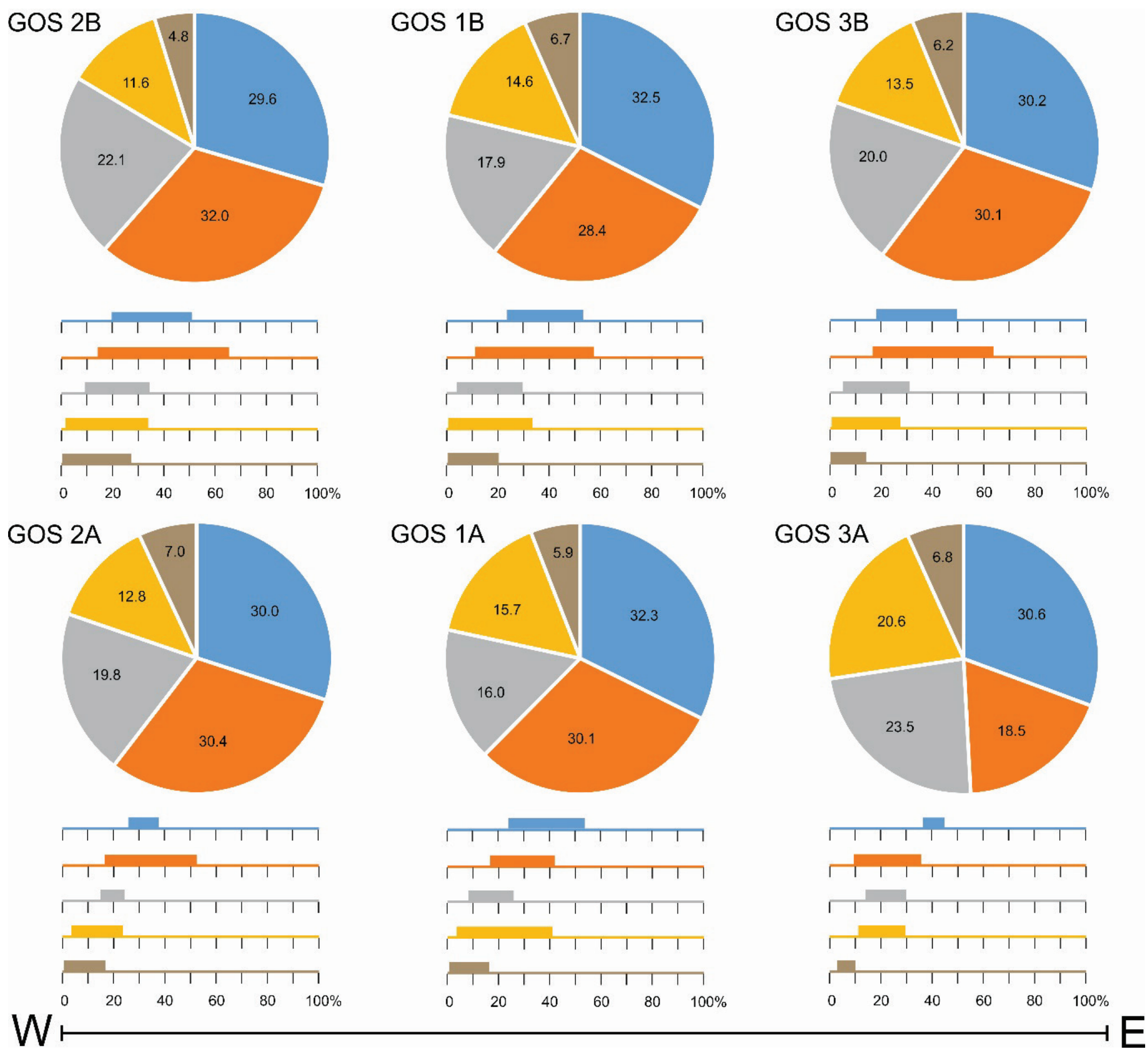

Figure 6. Properties of the sediment collected in the sedimentation traps in Lake Gościąż: average values and ranges (in percent). Organic matter (blue), calcium carbonate (orange), mineral residue (gray), terrigenous silica (yellow) and biogenic silica (brown). Epilimnion traps (GOS 2B, GOS 1B, GOS 3B), hypolimnion traps (GOS 2A, GOS 1A, GOS 3A).

4 Discussion

4.1 Spatial variation in sedimentation

Previous studies on sediment accumulation rates have shown cases of sediment both decreasing with increasing depth (Bloesch and Uehlinger, 1986; Botwe *et al.*, 2017) and the reverse (Kentzer and Żytkowicz, 1993; Ott *et al.*, 2018). In almost all cases, our study results on contemporary sediment accumulation rates in Lake Gościąż showed the amount of material deposited in traps increasing with depth. The only case of sediment accumulation rate in a trap installed in the epilimnion (in the GOS 2B trap) being greater than that in the hypolimnion (GOS 2A) occurred in July 2018, and may have been caused by an increased concentration of phytoplankton in the western part of the lake. This should be associated with the effect of the surface water layer being pushed or displaced by a strong easterly wind (gusts of up to 7.5 m s^{-1} for 3 days) at the end of June 2018. During the lake mixing (early spring and autumn) differences in the amount of sediment between the traps in the hypolimnion (A traps) and those in the epilimnion (B traps) were largest. More than once, especially in autumn, the amount of sediment in the A traps was more than double that in the B traps. During the summer stratification, when a well-established thermocline is a natural barrier to falling sediment (Lastein, 1976; Mieszczankin, 2004), the differences between the traps in the epilimnion and those in the hypolimnion were smaller. Similar relationships were noted during the research conducted on Lake Gościąż in 1991 (Kentzer and Żytkowicz, 1993) and in 1993-95 (Mieszczankin, 2004). Then too, summer quantities of sediment were similar at various depths, while in spring, and especially in late autumn, the rate of accumulation in the hypolimnion was several times greater than that in the epilimnion. The higher rate of sedimentation during the lake's overturn should be associated with an increased proportion of material from resuspension (Mieszczankin, 2004).

Assuming that the volume of primary production is similar in various places in such a small lake, the spatial variation in the amount of sedimentation is determined by other factors. In the case of lakes fed by river discharge, the influence of the density currents on the course and the distribution of sedimentation is greater (Lewis *et al*., 2002; Cohen, 2003; Schiefer and Gilbert, 2008). The significance of this factor may be dismissed in the case of Lake Gościąż. The small inflow (the average annual discharge is about 13 dm^3 s^{-1}), which disappears in summer and autumn, plays practically no role in supplying matter. In small, shallow lakes, this variability is mainly determined by the topography (Terasmaa, 2005) steepness of the lake basin (Blais and Kalff, 1995) and the distance of the measuring point from the shore (Bennett and Buck, 2016; Graham *et al.*, 2016). Higher sediment accumulation rates are found in a lake's deepest places, and in positions closer to the littoral zone. This is also true of Lake Gościąż. The lake basin morphology favours this. It consists of two steep-sloped basins (Fig. 1) separated by a clear threshold. This kind of the topography means that the sediment accumulation rate at the GOS 1 and GOS 2 stations is markedly higher than at GOS 3. This can be attributed to a "funnel effect", which involves the stream of falling particles increasing in concentration, translated into a higher sediment accumulation rate in the steepest zones of the lake basin. Material from the shallower parts of the lake being supplied can also not be discounted. Particularly favourable conditions in terms of sedimentation rate occurred at the GOS 2 site. This is due to the specific features of the location. The most important are the good sheltered of the local pool and the proximity of the littoral zone. The distal location of the site is also important, as it favours the supply of material from shallower parts of the lake via the action of internal waves along the bottom. This last factor has a particularly large impact on the course of sedimentation at the GOS 3 site. The supply of material from the littoral zone to the sediment trap, which is in the hypolimnion, is evidenced by the high share of mineral material in the sediment composition (Fig. 6).

During the 1991 study, the sediment accumulation rate at the deepest point of the lake averaged 8.65 g m^{-2} d^{-1}, while this value once reached 28.56 g m^{-2} d^{-1} (in October 1991). Sediment accumulation rate values in other months ranged from 1.84 g m^{-2} d^{-1} to 13.61 g m^{-2} d^{-1} (Kentzer and Żytkowicz, 1993) and were comparable with the 2017-19 results. This is indirect evidence that environmental conditions in the catchment are stable. Over the past 30 years there have been no changes in land use. Since 2001, Lake Gościąż's drainage basin has been protected as a reserve and human impact has been negligible. The form and structure of forest use has not changed in that time.

4.2 Seasonal variation in sedimentation cycle and its potential for varve formation and preservation

When examining the sediment accumulation rate in lakes, the local climate should be taken into consideration, since it may affect the seasonal variability of sedimentation. The amount of sediment can have either one or two peaks in a year and vary in duration. One commonly observed case is the clear increase in the amount of sediment in early spring. Sometimes this peak is persisted through the summer (Ott *et al.*, 2018; Johansson *et al.*, 2019). It can also happen that the peak occurs only in the summer (Bloesch and Uehlinger, 1986). Usually, however, two peaks – in early spring and autumn – can be found (Bonk *et al.*, 2015; Ott *et al.*, 2018). This last case applies to Lake Gościąż. The spring and autumn increase in sedimentation rate primarily result from increased primary production in the lake. This is favoured by the increase in air temperature in spring, the supply of nutrients from the lake bottom during periods of water mixing, and from the lake catchment in spring. According to our observations, a significant proportion of the material gathered in the sedimentation traps (especially traps in the hypolimnion) is redeposited from the lake basin.

The thermal conditions of Lake Gościąż are typical for dimictic water bodies. The temperature measurements showed clear thermal stratification from April 2018 to October 2018, and overturn in spring and autumn. Stratification and mixing periods significantly affect the amount of dissolved oxygen in the water column. Oxygen content is particularly important when considering the preservation of laminated sediments. For conditions to be conducive to preserving lamination, bottom waters should be devoid of, or relatively low in oxygen for at least part of the year (Anderson and Dean, 1988). The extent to which oxygen-free (anoxic) conditions are created is influenced by both how much organic matter is produced and the intensity of circulation in the water column (Kienel *et al.*, 2013). The relatively short period of anoxia in Lake Gościąż (from May 2018 to July 2018) may have adversely affected the preservation of sediment lamination. Compared to studies from the 1990s, when anoxia lasted from May to October, anaerobic conditions now last considerably shorter. However, detailed investigation by Bonk *et al*. (2021) showed that the annual lamination can be recognised in the sediment structure up to coring time (2015 CE).

The increase in the dissolved oxygen concentration below the thermocline observed in July 2018 and August 2018 is probably attributable to temporary circulation introduced by internal waves. Internal waves drive baroclinic shear instabilities that enhance the vertical turbulent diffusivity and reduce the rate of dissolved oxygen depletion in the hypolimnion (Bouffard *et al.*, 2014). Deep motions characterised by larger amplitudes at lower frequencies are favoured by the excitation of internal waves of the second vertical mode in strongly thermally stratified lakes (Valerio *et al.*, 2019). Internal waves are a common response to wind forcing in not only large but also small stratified lakes (Boegman, 2009). Internal waves at the density discontinuity border along the course of the thermocline are a record of short-term water temperature variations in the metalimnion (Thorpe and Jiang, 1998; Pannard *et al.*, 2011; Bonhomme *et al.*, 2011; Filatov *et al.*, 2012). Measurements taken in the middle of the lake (GOS 1) showed just such a temperature variability at a depth of 8 m (Fig. 4B). This can be considered indirect evidence of the occurrence of internal waves in Lake Gościąż.

In addition to the general effect that air temperature has on a lake's thermal and oxygen regimes, the short-term effects that meteorological parameters have on the hydrodynamic state of a lake should also be taken into account. In this regard, it is crucial to determine the effect of wind on lake mixing, the formation of internal waves, and the water circulation caused by their appearance. Increased water dynamics, not only in the epilimnion layer but also in the deeper layers of the lake, cause previously deposited sediment to be resuspended and increase the amount of material recorded in sedimentation traps. In Lake Gościąż, during the early spring and autumn, when the sediment accumulation rate increased, the prevailing winds were southerly and south-westerly. In the summer, when there was less sediment in the traps, northerlies prevailed. During prolonged strong winds, sedimentation increased, and in the GOS 2A trap in particular. When wind conditions were stable, the GOS 1A trap accumulated the most sediment, i.e. the one in the deepest studied location. The major impact of storm phenomena, when the strongest gusts were recorded, is visible in the course of sedimentation in the lake's western sub-basin (GOS 2A). The steep slope in the western part of the lake and the closeness of the sediment traps to the shore increased the supply of redeposition material. Internal waves formed under the influence of strong gusts of wind triggered the resuspension of material accumulated in the littoral zone and on the slope of the lake basin. The course of sedimentation was similar in the eastern part of the lake (GOS 3A), where the supply of material redeposited from the littoral zone is confirmed by the high content of terrigenous matter in the analysed samples.

The two-year investigation of lake productivity and weather conditions revealed clear, seasonal changes in sediment composition. Weather conditions have a direct influence on the water column, and thereby on variations in sediment composition. The sedimentation cycle starts when the ice cover begins to melt. Because the water density is uniform throughout the water column in that period, low wind speed is required to start the spring overturn (Löffler, 2004). Northerly winds (337.5°-22.5°) were the most frequent in spring in both study years and could have caused the intensive water column mixing (Fig. 2). Smear slides analysis suggests that green algae developed rapidly in spring (Fig. 5). The increased abundance of phytoplankton and rising temperatures caused, in turn, authigenic calcite production (Groleau *et al.*, 2000), which is visible in the increased $CaCO_3$ content (Fig. 6). As the heating proceeded, a thermocline developed and caused the development of the summer stratification of waters.

After the summer stratification, the epilimnion cooled down and, as a result, the temperature was the same throughout the water column. In autumn, southerly (157.5°-202.5°) and south-westerly (202.5°-247.5°) winds dominated, which caused the mixing of the water column to the bottom. The mixing could be the reason for the higher deposition and may be related to the remobilisation of nutrients, so the nutrients accumulated in the hypolimnion may have reached the surface layer of water and caused the phytoplankton bloom.

Reworked calcite forms agglomerates, in contrast to the single calcite grains that are newly precipitated in biochemical processes. The resuspended calcite grains were first observed in spring next to fresh grains. However, they were most abundant during autumn. The appearance of phytoplankton along with both types of calcite suggests a second calcite precipitation event and supports the idea of previously deposited material having been remobilised. It is not possible, however, to distinguish whether the resuspended calcite represents littoral sediments or comes from deeper slopes of the lake.

The seasonality in the course of sedimentation is partly reflected in water transparency measurements. Under conditions of thermal stratification, when the sediment accumulation rate was lowest, water transparency was highest. By contrast, water transparency was lowest during lake mixes, and during the spring peak in primary production, when the sediment accumulation rate was higher.

In dealing with the various factors that might affect the seasonal distribution of sedimentation, it was also necessary to consider how the lake water level fluctuated throughout the year (Lopez *et al.*, 2016). During the study period, however, this was minor, with the fluctuation amplitude not exceeding 40 cm. The weir on the stream Ruda, downstream of Lake Gościąż, moderates water level fluctuations in the lake. In connection with the above, this factor has a negligible role in the course of contemporary sedimentation in this area.

5 Conclusions

The results of this study show a spatio-temporal variation in sediment accumulation rate in the relatively small Lake Gościąż, Poland. The mean sediment accumulation rate in each of the three monitored locations was higher in the traps in the hypolimnion than in the traps in the epilimnion, as well as in locations with greater maximum depth. These results depend not so much on the spatial variation of the biological productivity of the lake, but mostly on the topography of the lake bottom (funnel effect). The seasonal variations were influenced by air temperature, and the speed and direction of the wind. These factors favoured the development of internal waves, which in turned caused an oxygen increase in the deeper parts of the lake. The confirmed relationship between sediment accumulation rate and both wind speed and direction indicates that relocated material is supplied to sediment traps, especially those located deeper. Redeposition of the material was also evidenced by the results of our analysis of smear slides and sediment composition. They showed that sediment composition is affected by season and the occurrence of strong north-westerly and south-westerly winds. The patterns and mechanisms of the course of contemporary sedimentation in Lake Gościąż, as determined based on the conducted investigations, can be applied in the study of other lakes and in assessing the representativeness of sampling sites for laminated bottom sediments to be used in palaeo-environmental studies.

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