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ORIGINAL PAPER

Sedimentological and geochemical responses of Lake Żabińskie (north-eastern Poland) to erosion changes during the last millennium

Alicja Bonk · Małgorzata Kinder · Dirk Enters · Martin Grosjean · Carsten Meyer-Jacob · Wojciech Tylmann

Abstract Increased erosion triggered by land-use changes is a major process that influences lake sedimentation. We explored the record of erosion intensity in annually laminated sediments of Lake Żabińskie, northeast Poland. A 1000-year-long, annually resolved suite of sedimentological (varve thickness, sediment accumulation rate) and geochemical data (scanning XRF, loss on ignition, biogenic silica) was analyzed with multivariate statistics. PCA indicated erosion was a major process responsible for changes in the chemical composition of the sediments. Analysis of sedimentary facies enabled identification of major phases of erosion that influenced lake sedimentation. These phases are consistent with the history of land use, inferred from pollen analysis. From AD 1000 to 1610, conditions around and in Lake Żabińskie were relatively stable, with low erosion intensity in the catchment and a dominance of carbonate sedimentation. Between AD 1610 and 1740, higher lake productivity and increased delivery of minerogenic material were caused by development of settlements in the region and widespread deforestation. The most prominent changes were observed between AD 1740 and 1880, when further land clearance and increased agricultural activity caused intensified soil erosion and higher lake productivity. Landscape clearance also created better conditions for water column mixing, which led to changes in redox conditions in the hypolimnion. The most recent period (AD 1880–2010) was characterized by partial reforestation and a gradual decrease in the intensity of erosional processes.

A. Bonk (✉) · M. Kinder · W. Tylmann
Faculty of Oceanography and Geography, University of Gdańsk, Bażyńskiego 4, 80952 Gdańsk, Poland
e-mail: alicja.bonk@ug.edu.pl

M. Kinder
e-mail: malgorzata.kinder@ug.edu.pl

W. Tylmann
e-mail: wojciech.tylmann@ug.edu.pl

D. Enters
Lower Saxony Institute for Historical Coastal Research, Viktoriastr. 26/28, 26382 Wilhelmshaven, Germany
e-mail: enters@uni-bremen.de

M. Grosjean
Oeschger Centre for Climate Change Research and Institute of Geography, University of Bern, Erlachstrasse 9a, 3012 Bern, Switzerland
e-mail: martin.grosjean@oeschger.unibe.ch

C. Meyer-Jacob
Department of Ecology and Environmental Sciences, Umeå University, 901 87 Umeå, Sweden
e-mail: carsten.meyer-jacob@umu.se

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Introduction

With the development of civilizations, especially since the introduction of iron tools, humans started to increasingly modify geomorphological and other natural processes (Messerli et al. 2000; Wilkinson 2005; Enters et al. 2008). One possible environmental consequence of human impact is increased erosion, triggered mainly by the intensification of land use, especially deforestation, cultivation and grazing (Bork and Lang 2003; Augustsson et al. 2013). Effects of these processes at lake catchment scales comprise not only direct changes in weathering intensity and sediment transport, but also indirect consequences such as changes in lake productivity caused by altered nutrient delivery, modification of the lake mixing regime, and transformation of ecosystem structure. Tracking the erosional responses to environmental change is thus important to fully understand ecosystem dynamics. Trends in erosion intensity, however, are difficult to determine on the basis of recent, short-term monitoring data (Dearing 1991). Long records are required to define and quantify the natural variability and the possible range of human-induced erosion.

Lake sediments are archives of erosional processes that occurred within the surrounding catchment (Edwards and Whittington 2001; Bork and Lang 2003; Enters et al. 2008; Arnaud et al. 2012). The sediment archive is most valuable when deposits are annually laminated (varved), which provides an accurate time-scale in calendar years (Brauer et al. 1999; Dörfler et al. 2012; Kinder et al. 2013; Zolitschka et al. 2015). High temporal resolution is important for studying past erosion over short timescales and for investigating environmental responses to abrupt events such as heavy rainfall, floods and intense soil erosion (Czymzik et al. 2013; Zolitschka et al. 2015). Moreover, a continuous, high-resolution timescale enables use of the sediment data to quantify these processes by calculation of sediment fluxes and estimation of the catchment sediment budget (Dearing 1991).

Sedimentological and geochemical investigations of sediment cores can provide vital information about past erosion intensity and its effects. Analysis of individual varve structures as well as disrupting layers (i.e. turbidites) can indicate the origin of the deposited material and changes in allochthonous sediment delivery to the lake. Different processes indirectly related to erosion in the catchment, such as changes in lake productivity and redox conditions, can be inferred using geochemical methods and element fluxes (Boyle 2001). Recent developments in analytical techniques, e.g. X-ray fluorescence (XRF) (Davies et al. 2015), Fourier transform infrared spectroscopy (FTIRS) (Meyer-Jacob et al. 2014) and hyperspectral imaging (Butz et al. 2015), have increased the potential for high-resolution and quantitative studies of sediment chemical compositions.

In this paper we present a sedimentological and geochemical record from Lake Żabińskie, a post-glacial lake located in northeast Poland that contains an undisturbed continuous sequence of annually laminated sediments (Tylmann et al. 2013). Recent limnological conditions and varve-formation processes in Lake Żabińskie, were investigated by Bonk et al. (2015a). Land-use changes in the catchment and the principal stages of lake development during the last millennium, were described by Wacnik et al. (2016). Using this unique sediment record and the results of previous investigations, our goal in this study was to assess how past changes in erosion intensity around Lake Żabińskie were recorded in the sediment lithology and chemical composition. To achieve this goal, we used an accurate varve chronology in conjunction with a set of annually resolved geochemical records, and analyzed them with multivariate statistics. We also compared our paleolimnological dataset with documentary sources and other available paleoenvironmental reconstructions.

Study site

Lake Żabińskie is located in the Masurian Lake District in northeast Poland (54°07′54″N; 21°59′01.1″E) at 117 m a.s.l. (Fig. 1). The surface geology of its catchment consists mainly of glacial sediments deposited during the maximum stage of the Vistulian (Weichselian) glaciation ca. 15.2 ka BP (Szumański 2000). The total catchment area (24 km²) consists of three sub-catchments related to Lake Żabińskie, Lake Purwin and Lake Łękuk (Fig. 1). The direct catchment of Lake Żabińskie is relatively small (∼2.3 km²) and extends mainly south of the lake. The northwest and southwest areas of the catchment are dominated by forests of pine, spruce and birch trees. Cultivated areas and wetlands

dominate the eastern part. The village of Żabinka, established in AD 1713, is located 0.5 km southwest of the lake. There is a recreation area on the north shore of the lake that was established in the years AD 1910–1920 and renovated several times since then (1950, 1970 and 1980s).

Lake Żabińskie has a small surface area (41.6 ha) and a maximum depth of 44.4 m. The lake has simple bathymetry, with the deepest point located in the middle of the lake. The lake is surrounded by steep slopes (Fig. 2) and has three inflows (I1–I3) and one outflow (O1), the latter draining southwest into Lake Gołdopiwo. Depending on meteorological conditions, however, i.e. strong winds from the west, water may episodically flow eastward from Lake Gołdopiwo into Lake Żabińskie. Depending on the air temperature and ice cover duration, Lake Żabińskie experiences different water-column mixing patterns (Bonk et al.

2015a). Spring and fall mixing is often incomplete, which leads to long periods of permanently anoxic conditions in the hypolimnion. Because of very stable thermal stratification, there are large differences between the surface- and near-bottom water masses. The hypolimnion is characterized by higher concentrations of major ions, nutrients and generally anoxic conditions, with only short periods of oxygenation.

Materials and methods

Core collection and correlation

A complete ∼348-cm sediment sequence, consisting of overlapping core segments, was collected from the deepest part of the lake during field surveys in 2011 and 2012. The short core ZAB-12/1 (48 cm) and ZAB-
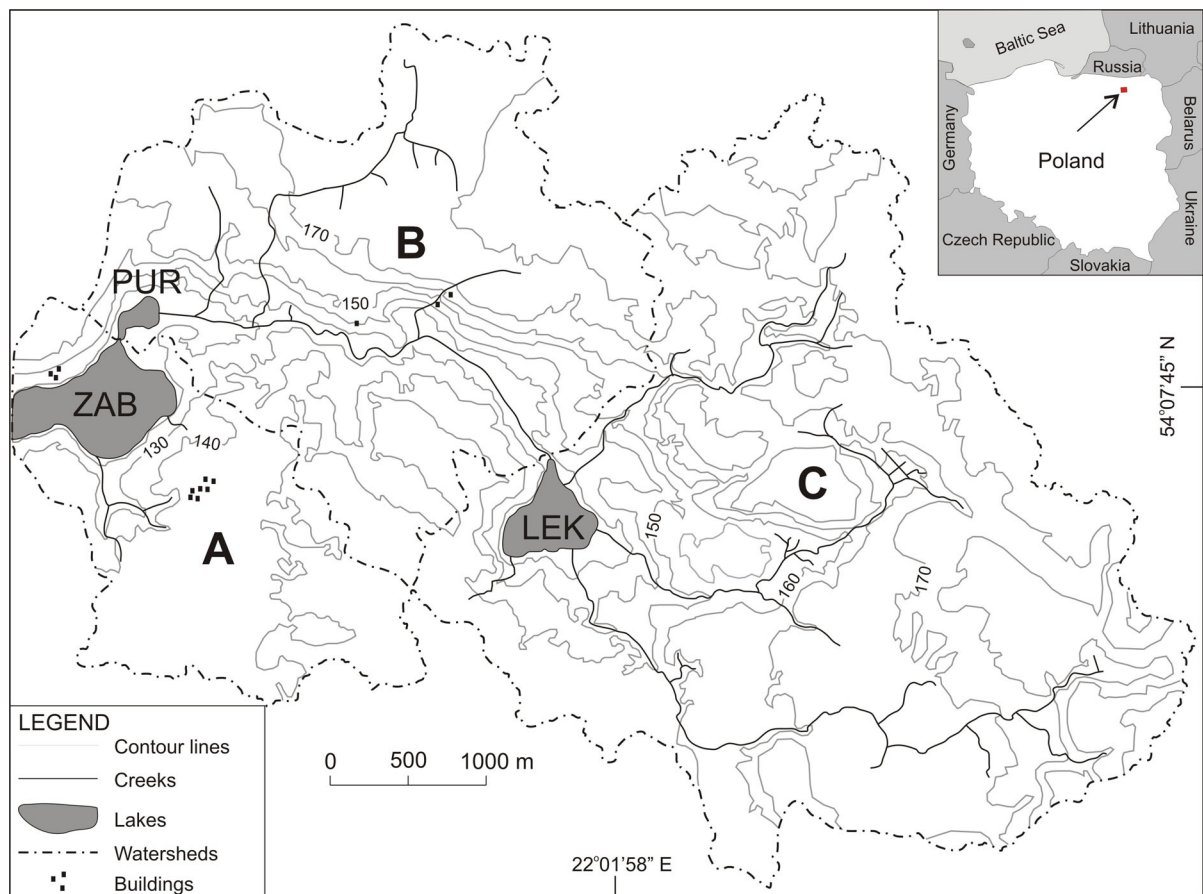

Fig. 1 Location and catchment of Lake Żabińskie. *A* sub-catchment of Lake Żabińskie (ZAB); *B* sub-catchment of Lake Purwin (PUR); *C* sub-catchment of Lake Łękuk (LEK)
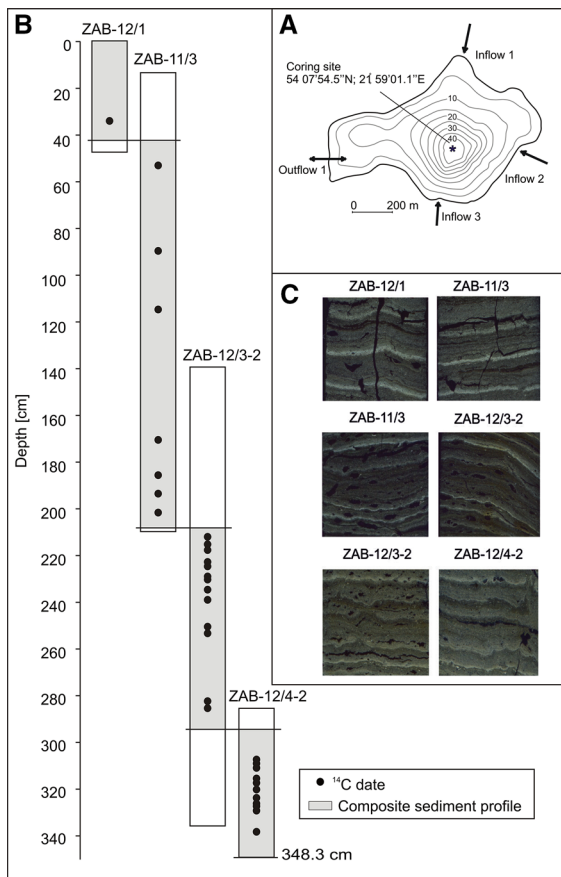
Fig. 2 Bathymetric contour map and coring sites (*A*); schematic diagram showing the correlation of individual cores (*B*) and examples of the microscopic correlation of thin sections (*C*)

11/3 (214 cm), with an undisturbed sediment–water interface, were recovered using a UWITEC gravity corer (Ø 90 mm); cores ZAB-12/3-2 (200 cm) and ZAB-12/4-2 (198 cm) were recovered using a UWI-TEC piston corer (Ø 90 mm). Immediately after collection, the cores were tightly capped, labeled and stored in cold conditions prior to analysis. In the laboratory, the cores were split lengthwise into two halves, described and photographed.

A continuous sediment profile was constructed by visual correlation of characteristic laminae in the overlapping sections of the cores. In each case, at least several marker layers were identified in the correlated cores, checked microscopically using thin sections and the number of varves between them was counted to ensure precise correlation and establish there were no sediment gaps (Fig. 2).

Chronology, varve structure and thickness

A detailed description of varve counting and the radiocarbon dating was presented by Bonk et al. (2015b). Varves were investigated microscopically at 20× to 500× magnification and different microfacies were recognized and described. Subsequently, varves were counted by three individuals, using high-resolution digital images of thin sections. Varve thickness (VT) was measured along three parallel lines (middle, left and right side of the thin section) to account for horizontal variability within a single varve, using CooRecorder software (http://www.cybis.se). The mean of three measurements was calculated and defined as the VT.

The varve chronology in the uppermost part of the sediment record was validated with ^{210}Pb and ^{137}Cs. Additionally, an independent geochronological marker, i.e. the Askja AD 1875 tephra horizon, was identified in the sample and dated by varve counting to AD 1872–1874 (Tylmann et al. 2016). Downcore, we used 21 ^{14}C dates to obtain a continuous radiocarbon-based age model (Bonk et al. 2015b). There is near-perfect agreement between the radiocarbon and varve chronologies from AD 1250 to present, whereas in the lower part of the sequence (AD 1000–1250) there is a discrepancy of about 25 years.

Elemental sediment composition

The split sediment cores were scanned using an Itrax XRF Core Scanner (Cox Analytical Systems) at GEOPOLAR (University of Bremen) to characterize the element composition along the length of the sections. Scanning was performed at a spatial resolution of 200 µm and 10 s count time using a Mo tube (30 kV, 18 mA). Elemental peak areas were normalized by coherent radiation to reduce sediment matrix effects (Croudace et al. 2006). Results of scanning are shown as an average value for each identified year (cts/coh). The depth in the sediment of each varve boundary was indicated precisely by microscopic analysis of thin sections and these depths were introduced to the XRF scanning data file to calculate average values for each year. Annual averages are comprised of between 2 and 76 XRF data points.

Subsampling for geochemical analyses was done with annual resolution based on varve boundaries established during varve counting. Relative proportions of organic matter (OM) and carbonates were measured

by loss-on-ignition (LOI) at 550 and 950 °C, respectively (Heiri et al. 2001). Calcium carbonate ($CaCO_3$) content was calculated by multiplying weight loss after combustion at 950 °C by 2.274, i.e. the ratio of the molecular weight of $CaCO_3$ and CO_2. Biogenic silica (BSi) concentrations were measured by Fourier transform infrared (FTIR) spectroscopy, according to the method described by Vogel et al. (2008). FTIR-spectral data were calibrated against wet-chemically measured BSi concentrations determined in 113 samples from Lake Żabińskie (3–70 %, as % SiO_2) using the method described by Ohlendorf and Sturm (2008). The internal calibration model relating FTIR-inferred and wet-chemically measured BSi values has a cross-validated R^2 of 0.82 and a root mean square error of cross-validation (RMSECV) of 5.7 %.

Data processing

Sediment components OM, $CaCO_3$, and BSi were transformed into fluxes (g cm^{-2} $year^{-1}$) using their percent concentrations and sediment accumulation rates (SARs), the latter calculated from VT and dry density of sediments. Using SARs avoids potential confounding effects of the matrix and compaction (Zolitschka 2003). To investigate the relationships between variables and reduce the data dimensionality we used multivariate statistical techniques (Jolliffe 2002; Reimann et al. 2008). Clustering and ordination were performed in the PAST 2.12 software (Hammer et al. 2001). Both analyses were applied to a set of variables including VT, SAR, OM, $CaCO_3$, BSi, K, Ti, Si, Ca, Sr, Fe and Mn. All data were log-transformed to stabilize their variances and time series were filtered with a 3-year triangular filter to account for possible errors in sampling. The dataset was analyzed using principal components analysis (PCA) to track the major changes in chemical composition over time. Because of the different units of the variables, a correlation matrix with a singular value decomposition (SVD) algorithm was used. Clustering was done using the unconstrained Ward's method, with the Euclidean distance as a similarity/dissimilarity measure (Murtagh and Legendre 2014). The unconstrained clustering enabled tracking transitional changes and comparing similar sequences instead of accepting the strictly defined boundaries between clusters. After defining the clusters, PCA analysis was performed for each cluster separately to investigate relationships between different elements and the processes behind changes in the chemical composition of the sediments.

Results

Down-core variability of sedimentological and geochemical features

All results are presented on a time scale with annual resolution (Fig. 3). VT, SAR and fluxes of major sediment components are relatively stable between AD 1000 and 1600. $CaCO_3$, however, displays a slight decreasing trend throughout this period. Variability of fluxes increases substantially up-core with different patterns for different components. OM flux shows an increase from around AD 1600 to 1650, followed by a decrease to a minimum around AD 1700. Fluxes of $CaCO_3$ and BSi show slightly increasing trends that start after the maximum in OM flux. OM and BSi fluxes show similar patterns, with maxima around AD 1790 and AD 1835. Large variability and an increasing trend in $CaCO_3$ fluxes are observed until AD 1880. OM fluxes increase gradually until a maximum around AD 1980, whereas $CaCO_3$ shows a more irregular record with a sharp decrease between AD 1880 and 1893. Another minimum is reached in the years AD 1950–1970, followed by a distinct maximum in AD 1979. Fluxes of all these components decrease in the last 25–30 years. In contrast, BSi fluxes decrease throughout the whole period since AD 1850, with only one distinct peak in AD 1977.

The XRF-detected elements do not change significantly until AD 1700, except for Fe, which has the highest values of the entire record around AD 1650, and Ca and Sr, which show decreasing trends. After AD 1700, the sediment profile is characterized by the highest variability of element counts. A significant increase is observed in K and Ti counts, which reach their maxima around AD 1850. Contributions of other elements increase slightly, except for the Fe counts, which show a general decreasing trend with a local peak around AD 1830. After AD 1850 a very similar development can be observed for K, Ti and Si counts, which decrease gradually to the top of the sediment record. Ca and Sr also show higher counts around AD 1850; afterward, Sr decreases steadily toward the top of the sediment record, whereas Ca decreases until AD 1900, but then starts to increase again. After AD 1900,
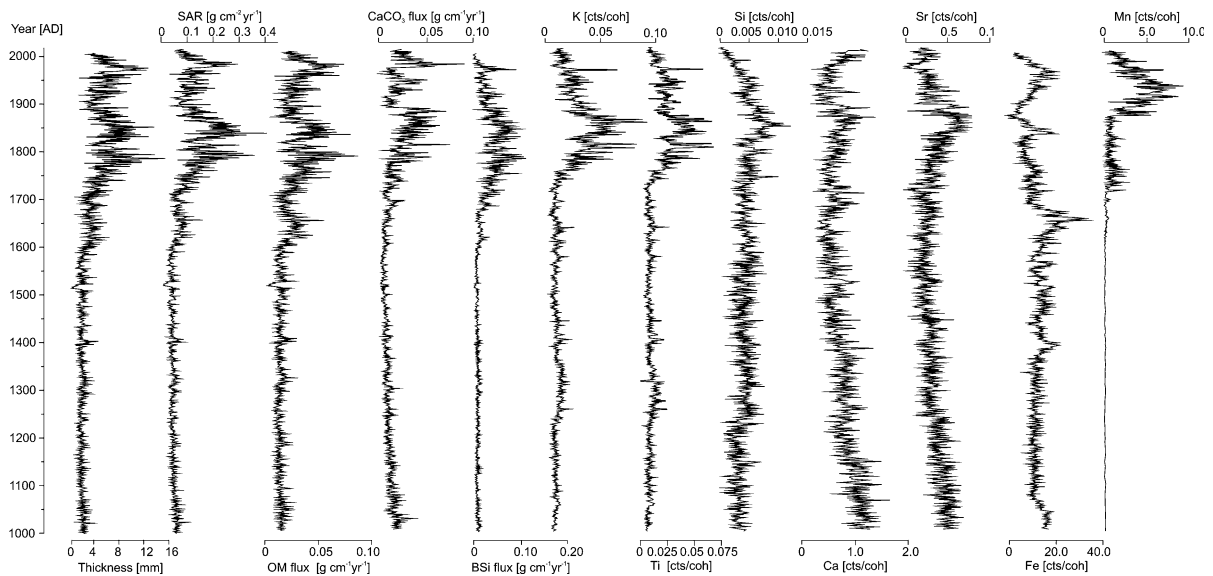
Fig. 3 Down-core variability of sedimentological and geochemical variables

the Fe counts increase to a localized maximum at AD 1950–1960, followed by a decrease toward the top. Mn counts show a pattern that is completely different from other proxies. Until AD 1700 low counts of Mn are detected in the sediments. From that time onwards, a slight increase is recorded until AD 1870 when a rapid increase leads to the localized maximum around AD 1900, followed by decreasing values toward the top of the sediment record.

Statistical analysis

The PCA on the whole dataset revealed the two components (PC1 and PC2) that explain >60 % of the total variance (Fig. 4). PC1 (40 % of variance) is mostly related to allochthonous inputs, represented by a strong positive correlation with Ti, K, SAR, VT and Mn (r > 0.5; Table 1). PC2 explains 20.8 % of the total variance and is mainly related to changes in carbonate sedimentation ($CaCO_3$, Ca, Sr).

Unconstrained clustering of the sedimentological and geochemical features of the varves resulted in four clusters that represent different sedimentary facies (Fig. 4). The PCA biplots for the individual clusters present the relationships between major sedimentological and geochemical features of samples belonging to each cluster and show compositional changes between the clusters (Fig. 4). In Cluster-1, PC1 is strongly positively correlated with elements related to carbonate sedimentation ($CaCO_3$, Ca and Sr), whereas PC2 is mostly related to VT and SAR (Tab.1). Indicators of erosion (Ti, K) play a minor role in the chemical composition of the sediments in this cluster. A distinct shift to higher correlations of PC1 with BSi, Ti and K is visible in Cluster-2. The role of erosion and in-lake production in the sedimentation regime is even more pronounced in Cluster-3. PC1 for this cluster shows strong positive correlations with K, Ti, Si and Sr. In contrast, PC2 represents sedimentation of carbonates, with highest correlations of $CaCO_3$ and Ca. In Cluster-4, PC1 is strongly positively correlated with Si, Ti, BSi, K and Mn. PC2 shows strong positive correlations only with elements associated with carbonates ($CaCO_3$, Ca and Sr).

Comparing the relationships between Si and other elements in different clusters provides insights into interactions between minerogenic inputs and in-lake (diatom) productivity. In Cluster-1 and Cluster-4, both sources are difficult to distinguish because Si is correlated with both erosion indicators (Ti, K) and BSi (representing diatom productivity). However, the position of Si in Cluster-2 and especially in Cluster-3 (high positive correlation with Ti and K, and negative correlation with BSi) clearly indicates erosion as a main source of Si in the sediments (Fig. 4).

The clusters are distributed sequentially along the core and, therefore, four general stratigraphic units can be established: ZAB-1 (AD 1000–1610), ZAB-2 (AD
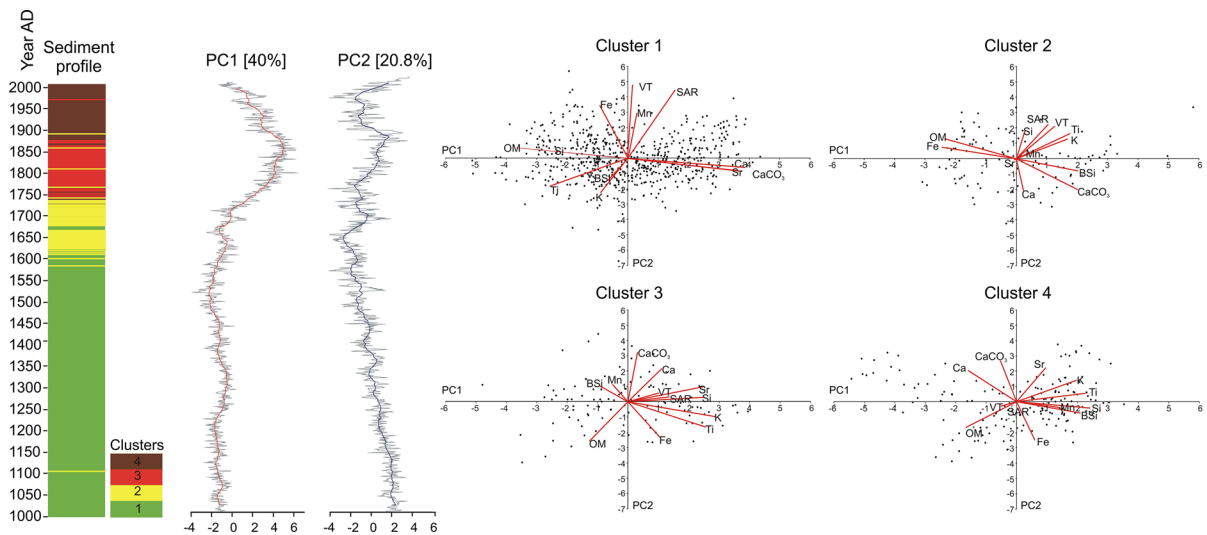
Fig. 4 Multivariate analysis of sedimentological and geochemical variables: (*1*) distribution of clusters (sedimentary facies) along the sediment profile; (*2*) distribution of PC1 and PC2 scores along the core; (*3*) biplots for individual clusters

Table 1 Correlations between datasets and PC1 and PC2 obtained for the entire sediment record and for four clusters (*p* < 0.01 marked in bold)

	Entire record		Cluster 1		Cluster 2		Cluster 3		Cluster 4	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
VT	**0.83**	**−0.12**	0.03	**0.79**	**0.45**	**0.62**	**0.31**	0.16	−0.19	−0.09
SAR	**0.86**	−0.02	**0.32**	**0.73**	**0.36**	**0.64**	**0.42**	0.08	−0.06	−0.09
OM	**−0.75**	**−0.47**	**−0.77**	0.11	**−0.79**	**0.36**	**−0.39**	**−0.70**	**−0.62**	**−0.50**
CaCO₃	0.03	**0.85**	**0.84**	−0.16	**0.68**	**−0.58**	0.10	**0.88**	−0.20	**0.79**
BSi	**0.47**	−0.18	−0.14	−0.24	**0.68**	−0.22	**−0.29**	0.28	**0.77**	−0.21
K	**0.88**	0.06	−0.19	**−0.37**	**0.58**	**0.37**	**0.88**	−0.26	**0.74**	**0.42**
Ti	**0.88**	**−0.13**	**−0.54**	**−0.30**	**0.60**	**0.47**	**0.78**	**−0.45**	**0.84**	0.16
Si	**0.42**	**−0.31**	**−0.46**	0.07	0.09	**0.50**	**0.77**	0.08	**0.90**	−0.12
Ca	**−0.20**	**0.84**	**0.80**	−0.10	0.08	**−0.60**	**0.34**	**0.59**	**−0.59**	**0.60**
Sr	**0.20**	**0.73**	**0.82**	−0.15	−0.03	−0.02	**0.76**	**0.26**	**0.36**	**0.66**
Fe	**−0.48**	**−0.36**	−0.19	**0.57**	**−0.84**	0.21	**0.32**	**−0.63**	0.22	**−0.73**
Mn	**0.75**	**−0.16**	0.07	**0.49**	0.08	0.06	−0.16	**0.30**	**0.54**	−0.12

1610–1740), ZAB-3 (AD 1740–1880) and ZAB-4 (AD 1880–2010). Unit ZAB-1 covers the lower part of the sediment record and represents a homogenous structure with only incidental presence of sedimentary facies from Cluster-2. The transition to ZAB-2, marked by mixed sedimentary facies, indicates the time ca. AD 1580–1610 as a period of major change. The most prominent increases are observed for SAR, Fe counts and BSi contents. Units ZAB-2 and ZAB-3 are more heterogeneous and contain varves that

belong to different sedimentary facies (Fig. 4). The most prominent changes in the transition zone between these units (ca. AD 1730–1770) are rapid increases in SAR values and Ti counts. Other proxies are more variable, although no unambiguous trend is observed. The transition from ZAB-3 to ZAB-4 (ca. AD 1860–1890) suggests more gradual changes. SAR and Ti contents decrease while the Mn counts increase remarkably. The Fe counts and BSi contents are variable and display no significant trend.

Structure and chemical composition of varves

Investigations of thin sections allowed for the determination of the composition of laminations and their classification as calcite-type biogenic varves. The structure and chemical composition of individual varves change with sediment age, and typical features can be distinguished for the four stratigraphic units (Fig. 5):

- Varves typical for ZAB-1 show well-preserved, regular and relatively simple structures. Most of the varves consist of two or three laminae: (1) a spring calcite lamina, (2) a grayish lamina (occasionally) that contains small calcite grains and biogenic remains and (3) a dark detrital lamina characteristic of winter sedimentation. In some of the varves, laminae (2) and (3) are difficult to distinguish and instead form one rather mixed lamina. Element peaks occur regularly, starting with the most prominent Ca peak that marks spring/summer calcite precipitation. It is followed by slightly increased Fe counts, which may indicate fall mixing. The Ti content is low, although a small peak usually occurs at the end of the annual cycle. The mean VT in this unit is 2.2 ± 0.6 mm.

- Varves from unit ZAB-2 are characterized by a structure similar to ZAB-1, but the VT is greater and the preservation is poorer. The typical varve

consists of (1) a distinct spring calcite lamina, (2) an olive-brownish lamina mainly composed of diatoms and small calcite grains, and (3) a blackish lamina composed of organic and minerogenic detritus, representative of winter deposition. A slightly higher Fe content (early spring mixing) precedes the Ca peak related to spring/summer calcite precipitation. Next, a major Fe peak occurs and likely marks the fall mixing period. In contrast to ZAB-1, Ti content shows more variation, with several small peaks that may indicate repeated erosional pulses throughout the year. However, the absolute values of Ti counts are generally low and the variation observed might be influenced by analytical noise. Another difference compared to ZAB-1 is the higher VT in ZAB-2, which reaches values up to 7 mm (mean 3.7 ± 1.1 mm).

- In ZAB-3, typical varves are very thick and poorly preserved compared to the previous units. A single varve consists of (1) a thin calcite lamina that marks spring deposition, (2) a much thicker grayish layer with different numbers of sublaminae and occasionally (3) a thin clay lamina deposited at the end of the annual sedimentation cycle. The chemical structure shows a Fe peak that marks the early spring mixing. Next, a small Ca peak indicates calcite precipitation during late spring and early summer. The wide and prominent peak of Ti reflects high terrestrial input over the whole year, but deposited on the lake
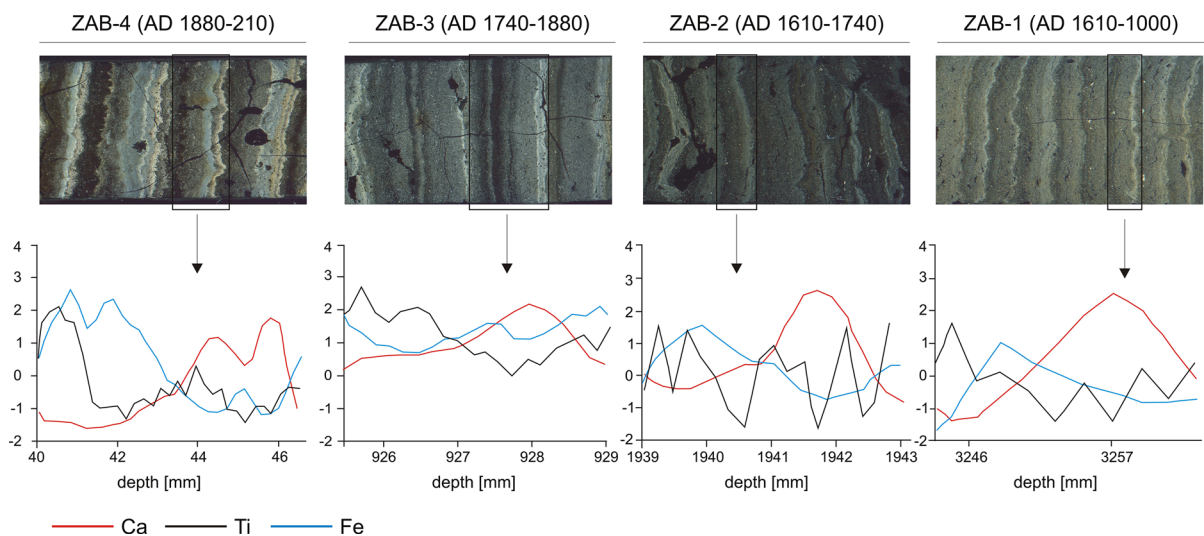

Fig. 5 Variability of selected chemical elements in different varve microfacies. The length of each photo is 2.5 cm. The horizontal scale in millimeters refers to the total sediment depth of the composite profile, the vertical scale shows normalized values (with respect to mean and standard deviation for each stratigraphic unit)

bottom at the end of sedimentation cycle. The VT is very high, with a maximum value of 15.5 mm (mean 6.8 ± 2.6 mm).

- Varves of ZAB-4 exhibit the most complex structure and have excellent preservation. The varve boundaries are very clear and different numbers of individual laminae can be distinguished in different years (up to four calcite laminae). A characteristic annual succession of chemical elements follows the pattern: (1) spring is marked by slightly higher Fe counts (spring mixing), followed by a major Ca peak (calcite precipitation); (2) during summer and fall, minor Ca peaks occur (multiple periods of calcite precipitation); (3) the maximum in Fe is observed during the second half of the year (fall mixing); (4) the winter period is characterized by a peak in Ti. The maximum VT in this part of the core is 12.8 mm (mean 5.7 ± 2.3 mm).

Discussion

Long-term trends in erosion intensity and their local conditions

Cluster analysis of the sediment record indicates four major stratigraphic units characterized by different sedimentological and geochemical features of the sediments. PCA analysis of the whole dataset, as well as PCA of individual clusters, showed that erosion was the most important environmental process responsible for those changes (Fig. 4). The transitions between the stratigraphic units are very clear and consistent with the settlement history and land-use changes in the region inferred from pollen analysis (Wacnik et al. 2016).

ZAB-1 (AD 1000–1610)

During the first six centuries of the last millennium, erosion intensity remained at low levels with only minor fluctuations as indicated by PC1, which is mostly correlated with the erosion indicators. This finding is not surprising in light of the results of pollen analysis (Fig. 6), which show that the lake catchment and surrounding areas were covered by forest until AD 1450, when only small-scale deforestation and slight

increases in agricultural activity began (Wacnik et al. 2016). Historical documents show that the local settlements developed more intensively in the second half of the sixteenth century (Białuński 2002). Shortly thereafter, a major transformation from a highly forested to a more open landscape with intensive farmland was registered in the pollen data (Fig. 6). As a result, the erosion rates started to increase slightly, causing changes in the lake ecosystem stability and sediment composition. Gradual increases in SAR values and BSi content suggest higher in-lake production. Yet the transport of minerogenic material from the catchment remained at low levels, as shown by only minor variations in Ti counts in the transition zone between ZAB-1 and ZAB-2. These minor changes indicate that deforestation did not occur in the lake catchment proper, but rather in more distant areas.

ZAB-2 (AD 1610–1740)

After deforestation in the region and a substantial increase in agricultural activity, erosion rates became more variable and increased gradually (Fig. 6). The effect of forest clearance is well documented by a progressive decrease in the arboreal pollen (AP) curve. The fluctuations in erosion intensity might have been associated with changes in population density and other historical factors, e.g. military operations and plagues, which affected the Masurian Lake District several times (Töppen 1870; Kossert 2009). The most dramatic increase in erosion rate occurred at the end of this period and was related to the establishment of the village of Żabinka in AD 1713 (Wakar and Wilamowski 1968). Because the village is located only ~ 0.5 km from the lake, further deforestation and development of arable lands occurred in the immediate vicinity of the lake. This caused the most pronounced increase in erosion indicators starting around AD 1720–1730 (Ti, K; Fig. 3). A general transformation of the chemical sediment composition is expressed by the PC1 shift toward higher values, as well as a substantial change in sedimentation rate (Fig. 6).

ZAB-3 (AD 1740–1880)

During this period, PC1 loadings reached maximum values, reflecting the most intensive erosion in the lake
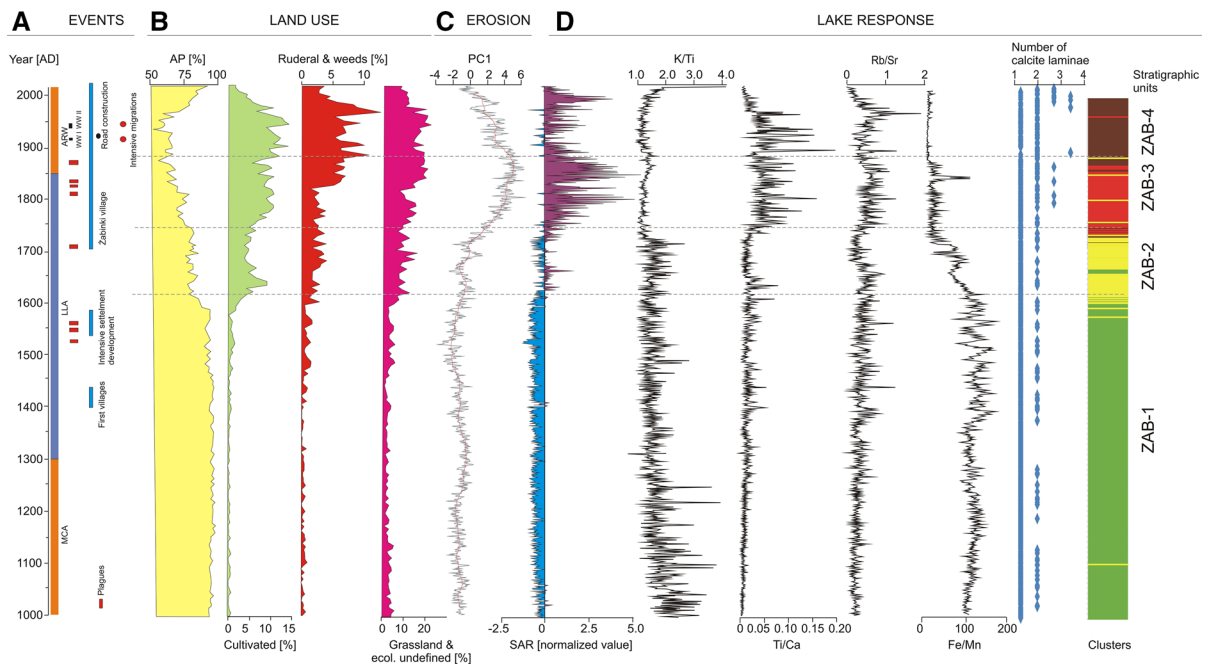
Fig. 6 Sedimentological and geochemical variables inferred from varves of Lake Żabińskie versus land-use changes. *A* Chronology of major historical events and climatic periods. *B* Major pollen indicators of land-use change (Wacnik et al. 2016). *C* Intensity of erosion reflected by PC1. *D* Selected sedimentological variables and geochemical ratios as lake responses to changes in land-use

catchment (Fig. 6). This increase is likely correlated with agricultural development, which became most prominent after AD 1810, when arable lands were likely to have reached the lake shore (Wacnik et al. 2016). After the peak in erosion around AD 1855, a slight decrease in the PC1 loadings, together with an increase in the arboreal pollen, suggests a reduction in agricultural practices toward the end of this unit. This was almost synchronous with the emigration period, when many people left the area because of prolonged unfavorable weather conditions (Töppen 1870). The transition to the next unit is characterized by decreasing SAR, related mostly to reduced delivery of minerogenic material from the catchment. In the second part of the nineteenth century, the construction of canals between lakes in the Masurian Lake District was common and led to lowering of water level in many lakes. For instance, the water level in adjacent Lake Kruklin was artificially lowered by ∼6 m during the 1840s, through a connection with Lake Gołdopiwo (Srokowski 1945). Water-level changes might also have contributed to erosion changes recorded in Lake

Żabińskie, because exposed lake shores without stable vegetation could have been intensively eroded during heavy rainfall events.

ZAB-4 (AD 1880–2010)

The onset of the most recent phase of the Lake Żabińskie development is characterized by the decreasing role of erosional processes. This trend was related to a very unstable period for settlement in the Masurian Lake District (World Wars I and II), which also caused stagnation of agriculture. Moreover, Lake Żabińskie was isolated from much larger Lake Gołdopiwo after road construction between the lakes in AD 1923–1924. Despite incidental peaks in the erosion indicators, e.g. in the 1970s (Fig. 3), a steady decrease in the role of erosion was observed during the last few decades. Agricultural abandonment in recent decades caused transformation of crop lands into meadows and reforestation of the lake shores (Wacnik et al. 2016).

Effects of erosion on in-lake processes and sedimentation

Erosion can affect lake sedimentation directly by delivery of minerogenic material and organic particles from the catchment to the lake basin. However, soil erosion in the catchment also conveys additional chemical elements and nutrients to the lake, thus influencing the lake trophic status (productivity), redox conditions in the water column, the chemical composition of sediments and sedimentation rates. Both direct and indirect influences of changing erosion intensity are visible in the sediment record from Lake Żabińskie. Small differences in the timing of land-use changes, as indicated by pollen, and erosional responses visible in the sediment, can be explained by the regional (pollen) versus local (erosion) nature of the phenomena.

Carbonate sedimentation, with only minor minerogenic inputs, played the major role until the end of the sixteenth century, i.e. when the lake catchment remained covered by dense forests (Fig. 6). Landscape destabilization around AD 1600, as recorded by pollen, caused first an increase in detrital inputs, as indicated by minor variations in the Ti and K contents, as well as pronounced peaks in the Ti/Ca ratio. Human disturbances in catchments, resulting in soil destabilization and changes in erosion patterns, have been documented in numerous paleolimnological studies using the above proxies (Arnaud et al. 2012; Aufgebauer et al. 2012; Balascio et al. 2011; Boës et al. 2011; Corella et al. 2012; Martin-Puertas et al. 2012). The Ti/Ca ratio, in particular, provides useful information about higher erosion intensities in the lake catchment (Litt et al. 2009). After the first landscape destabilization, maximum erosion intensity is well documented during the ZAB-3 phase by huge increases in SAR and Ti/Ca. Also, the Rb/Sr ratio, which may be an indicator of chemical weathering intensity (Fernández et al. 2013), shows a similar pattern. This ratio can also indicate sources of material transported to the lake. Landscape opening and related soil exposure to erosion may have caused enhanced transport of weathered soil particles (higher Rb/Sr values). In contrast, lower Rb/Sr values could indicate more intense delivery of unweathered particles, e.g. lithogenic material mobilized from creek bank erosion. The K/Ti ratio decreases substantially in ZAB-3, compared to ZAB-1 and ZAB-2. Potassium is more likely to be associated with fine-grain particles (clays), whereas titanium is associated with coarser grain sizes, i.e. the silt or sand fraction (Marshall et al. 2011). Therefore, the K/Ti decrease may indicate increased delivery of coarser material from the catchment, which is also visible in the sediment lithology.

Landscape transformation in the catchment of Lake Żabińskie also caused important changes in the water column, as shown by the Fe/Mn ratio (Fig. 6). This ratio has been used frequently to reconstruct past redox conditions in the near-bottom waters (e.g. Corella et al. 2012; Naeher et al. 2013). High values of the Fe/Mn ratio prior to AD 1600 are a consequence of the low levels of Mn in these sediments (Fig. 3). The high and relatively stable values of Fe/Mn during this period can thus be explained by permanently low oxygen availability in the near-bottom waters. This is supported by the low exposure to wind of this small and deep lake located, at that time, in a completely forested catchment. Such a well-sheltered lake basin favors incomplete water-column mixing and perhaps meromixis (Tylmann et al. 2012). The situation started to change after initial deforestation of the catchment, and the Fe/Mn ratio decreased gradually to much lower values in the eighteenth century. This can be explained by landscape opening, which led to higher wind exposure of the open-water area and better mixing of the water column. Seasonal presence of oxygen in the hypolimnion enabled gradually increasing Mn deposition between AD 1600 and 1650 and, as a consequence, a drop in the Fe/Mn ratio. During the eighteenth and nineteenth centuries, the Fe/Mn ratio stabilized at much lower levels than prior to AD 1600, with only one incidental peak recorded around AD 1830. Despite our interpretation, we acknowledge that changes in Fe and Mn are difficult to interpret because of a number of independent factors that control their supply and sedimentation (Engstrom and Wright 1984; Fernández et al. 2013). In our case, however, major shifts in the Fe/Mn ratio coincide with prominent changes in detrital inputs. Peaks in Fe counts and related increases in the Fe/Mn ratio around AD 1830 are consistent with peaks in K and Ti, which indicate that detrital inputs might have been responsible for that change. A similar influence of Fe supply from terrigenous sources has been shown in Lake Rotsee in Switzerland (Naeher et al. 2012).

Changes in erosion intensity affect SARs (Simonneau et al. 2013). However, SAR is controlled by many factors and depends not only on erosion rates, but also on changes in lake productivity, which in turn might be influenced and enhanced by soil erosion (Ott et al. 2005). Agricultural practices in particular can significantly alter nutrients and carbon cycling as a consequence of soil erosion (Quinton et al. 2010). In the case of Lake Żabińskie, variations in SAR until the twentieth century are consistent with land-use transformations and related changes in erosion intensity (Fig. 6). After AD 1600, SAR increased by a factor of two in ZAB-2 and by almost a factor of four during the maximum of erosion intensity in ZAB-3 (AD 1740–1880). The response to the landscape opening was the tripling of $CaCO_3$ and BSi fluxes by the mid-nineteenth century, which reflects intensified in-lake productivity related to increased nutrient input from agriculturally used soils in the immediate catchment. Similarly, Veski et al. (2005) found that the land clearance had a major influence on erosion rates and SAR variability in Rõuge, southern Estonia. In Lake Żabińskie, however, this relationship did not hold during the twentieth century: while the erosion intensity decreased, SAR increased steadily until the late 1970s. This tendency changed only in the most recent decades. Thus, the twentieth century increase in SAR must have been caused by changes in lake productivity, independent of soil erosion and probably related to the use of fertilizers or nutrient delivery from the recreation area established on the northern shore of the lake. Although global forcing such as climate warming, changes in hydroclimate and the nitrogen cycle (Wolfe et al. 2013) might have also contributed to the SAR variability in Lake Żabińskie, it is difficult to tease out a clear signal of global processes because of the strong overprint of regional and local human activity.

Apart from changes in the chemical composition and sedimentation rates, erosion also influenced the structure of varves deposited in Lake Żabińskie. The period of carbonate sedimentation and stable redox conditions between AD 1000 and 1600 (ZAB-1) is reflected in thin, perfectly preserved varves with one distinct calcite lamina (Fig. 5). The structure of varves from ZAB-2 is similar, but the VT is substantially higher. Also, the chemical composition suggests more variable inputs of minerogenic particles transported from the catchment.

The dramatic increase in catchment inputs during ZAB-3 is reflected in very high VT, the presence of clay laminae and high contents of Fe and Ti. An increase in lake productivity during the latest stratigraphic unit (ZAB-4) is reflected in the varve structure by multiple calcite laminae. However, a general decrease in erosion intensity and reduced detrital inputs resulted in a decrease in VT during the most recent decades.

Conclusions

We investigated sedimentological features and the chemical composition of the continuously varved sediment profile from Lake Żabińskie with the aim to assess how changes in erosion intensity in the catchment were recorded in the sediment. We used a set of annually resolved sediment variables, analyzed with multivariate statistics, and compared our results to historical and pollen data. The conclusions can be summarized as follows:

- We identified four phases of different erosion intensity related to human-induced transformations in land cover and agricultural activity.
- Changes in land use documented by pollen analyses caused substantial shifts in the sedimentation regime, manifested mainly by a change in the contribution of detrital inputs after deforestation and agricultural development.
- The above changes had a strong influence on SARs and element fluxes, which increased up to four times compared to values prior to deforestation.
- The sediment Fe/Mn ratio suggests that landscape opening might have caused more intense wind-mixing of the water column, and in turn, better oxygenation of the hypolimnion in Lake Żabińskie.
- Changes in the varve structures were observed, along with changes in erosion intensity, and the former were manifested mainly by an increase in VT and deposition of clay laminae. Large instability of environmental conditions during the twentieth century caused a more complex structure of the deposited varves.

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