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Lithological and geochemical record of anthropogenic changes in recent sediments of a small and shallow lake (Lake Pusty Staw, northern Poland)

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Abstract

The article presents the results of lithological and geochemical investigations of recent sediments of Lake Pusty Staw. The analysed sediments document about 300 years of the history of this lake. Historical materials indicate that significant changes in the catchment of the lake took place from the beginning of the 18th century (deforestation and afforestation) followed by 19th century tourist development, and 20th century industrialisation. The sediments were dated using the ^{210}Pb and ^{137}Cs method and core lithology. These made it possible to establish a reliable chronology to the year 1730. The calculated sedimentation rates ranged between 0.17 and 0.83 cm year^{-1}. There was a period of intensified erosion caused by land clearance between 1734 and 1810, which resulted in an acceleration in sedimentation rate (0.36 cm year^{-1}) and a change of lithological type of sediment from detritus gyttja to clayey gyttja. On the basis of Cu, Zn, Cd and Pb content in the sediments, it was determined that the beginning of pollution of the lake dates back to the 19th century and was caused probably by the existence of a health resort. A systematic increase in pollution occurred in the 20th century as a result of industrial plants. Normalised with respect to Al, the content of heavy metals in polluted sediments was from several to twenty times higher than in sediments of the preindustrial period, and a comparison of historical materials with changes of sediments in most cases made it possible to identify the direct causes of the increase in pollution.

Introduction

Together with the progress of civilisation, changes in the natural environment caused by man play a growing role. An especially interesting period is the last several hundred years due to a large increase in human activity from the beginning of the 19th century related to the industrial revolution. In this period, the economic development became the cause of far-reaching changes in the land use and introduction of large quantities of pollution to the natural environment, which resulted in a progressive degradation of the natural environment, especially in the second half of the 20th century. Because monitored water analyses are confined to comparatively recent time, paleolimnological analyses of sediment cores can help track changes in the environment caused by man's activity. A wide spectrum of environment change indicators and dating methods make it possible to determine both the time of occurrence of changes as well as their scope and intensity.

Numerous sources of information, such as historical documents and cartographic materials facilitate the identification of direct causes of environmental changes.

The objects which are strongly transformed by man are lakes located in immediate surroundings of large urban areas or industrial plants. A clear record of intense industrialisation, urbanisation and motorisation processes in such reservoirs has been found in many studies (e.g., Digerfeldt et al. 1980; Foster et al. 1991; Charlesworth and Foster 1993, 1999; Van Metre and Callender 1997; Aström and Nylund 2000). Especially susceptible are small and shallow lakes which react the quickest and undergo unfavourable transformations most easily.

The purpose of this study was to document changes in sediment lithology and geochemistry of a lake basin relative to known historical disturbances in the catchment caused by spatial development of Gdańsk. The chosen lake is located within the boundaries of a big city (about 0.5 million inhabitants) near numerous industrial estates, and was remained under considerable human influence for at least about 300 years. These changes covered deforestation of the catchment, afforestation and gradual development of a health resort, followed by development of industry. A clear record of the changes was obtained using sedimentological and geochemical analyses of recent sediment cores. The sediments were also subject to palynological analyses whose results will be presented elsewhere.

Study site

Present day situation

Pusty Staw (longitude 18°21′51″, latitude 54°43′25″) is a WSW to ENE elongated lake without outflow (Figure 1), which is probably an abandoned oxbow of the Vistula River. Today it is a small lake (7.5 ha) filling a water-logged depression surrounded by dunes. The altitude of water surface is about 1.5 m above the sea level, and the lake basin has a slightly diversified character with quite steep shores and a wide, flat central area. Maximum depth is about 3 m. The lake basin is partially filled with lake sediments, mainly homogenous, dark brown detritus gyttja of thickness between 260 and over 400 cm (Tylmann 2003). The base of the lake sediment is non-lacustrine sands of various grain sizes.

The catchment area of Pusty Staw is very small (< 100 ha) and presently about 90% is covered by forest. In waterlogged areas the dominating community is *Alnus*, in drained areas *Betula*, *Fagus* and *Pinus* occur. The remaining 10% is made of urbanised areas in the form of dense municipal building development.

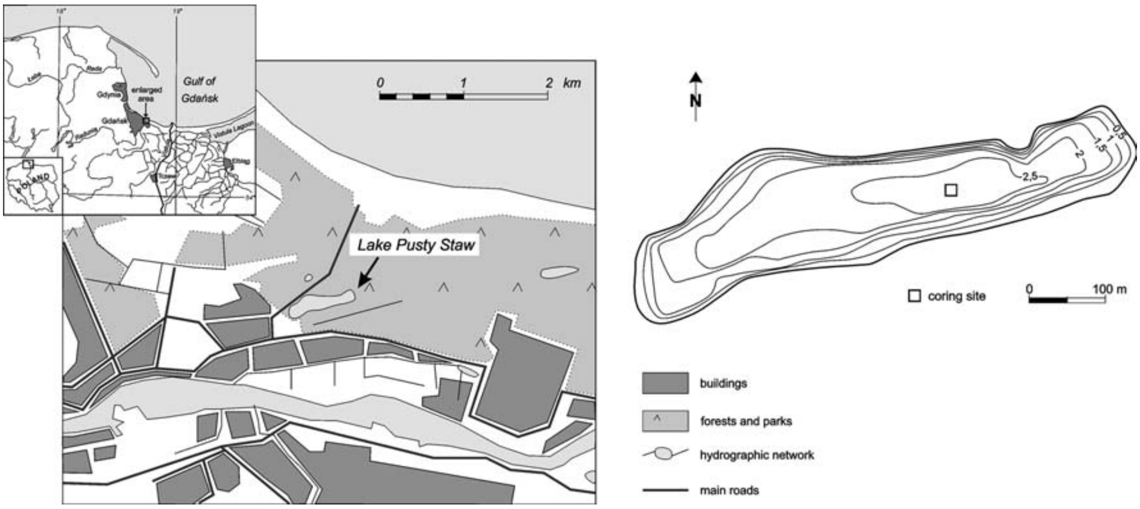

Figure 1. Location and bathymetry of the study site.

Historical background

From the 13th century in the immediate vicinity of Lake Pusty Staw there existed a fishing settlement and later the village of Stogi. According to historical sources, Pusty Staw was then surrounded by thick forest areas. Considerable changes caused by human activity took place already in the 18th century when, as a result of warfare, the outskirts of Gdańsk were destroyed, and a large part of forests around Pusty Staw was burned (Stankiewicz 1993). The situation of that period is presented on a map from 1769 showing the location of the village and lands belonging to it (Figure 2a). Despite the quite poor preservation of the map there can be seen a deforested area in the western and northern part of the catchment. The afforestation began in 1795 and continued in the first half of the 19th century.

The beginning of the 19th century brought other warfare related to Napoleonic Wars (1807–1813). In 1807 battles took place near Pusty Staw during the siege of Gdańsk by French troops. In 1812 the Napoleonic army was stationed near Pusty Staw and a year later there was heavy fighting using artillery (Zajewski 1993). Important spatial changes in the catchment of Pusty Staw and its surroundings occurred after the end of warfare. A Health Centre established on the lake shore after afforestation of the terrain around the lake started the tourist development of the settlement. A hastening of the development of industry occurred in the beginning of the 20th century when the buildings of the former health resort were transformed into a haberdashery plant, which worked till the beginning of World War II (1939–1945). In the second half of the 20th century, the recreational character of the area on Pusty Staw was ultimately destroyed; a large housing estate was built, and the haberdashery plant became the main source of pollution, probably to a large degree discharging directly into the lake. The development of industry between 1960 and 1970 resulted also in the construction of several large industrial chemical plants in this part of Gdańsk. At the beginning of 1990, the industrial plants considerably decreased their production, and environment protection norms forced a limitation of the emission of pollutants. Thus it may be assumed that man's pressure has substantially decreased since then.

Methods

Coring and subsampling

Four cores of recent sediments (over 100 cm of thickness) were taken from a pontoon boat using the Beeker sampler (Eijkelkamp), a piston corer adapted to taking samples of unconsolidated sediments and providing an undisturbed structure and low compression of material (Ananymous 1999). The cores were taken from the central flat area of the bottom so as to obtain a record more representative of the whole lake (Digerfeldt 1979; Smol 2002). Then they were subsampled at 2 cm intervals using a pressure pump. Tightly packed samples were transported to the laboratory and stored at 4 °C until the analyses.

Laboratory analysis

As several cores were used, a necessary action was a correlation of the cores so as to avoid errors related to a shift of layers with respect to each other as a result of natural variation in accumulation rate and errors in coring and subsampling. The cores were correlated on the basis of the content of organic matter and lithological features of the sediment. It was possible to distinguish a unit of brownish-grey clayey gyttja in all of the cores, however the boundaries between the units were not sharp. More detailed information was achieved on the basis of organic matter content (Figure 3), establishing good cross correlation between the cores. Sediment samples from the main core PS01/1 were used for age determinations (^{210}Pb and ^{137}Cs), samples from the core PS01/2 for geochemical analyses and from the core PS01/3 for particle size determinations.

The main core was dated at the Marine Radiochemistry Laboratory IO PAS in Sopot using ^{210}Pb, and then the time scale was verified by ^{137}Cs. ^{210}Pb was determined indirectly by measuring ^{210}Po in α-spectrometer. Markers ^{209}Po and ^{133}Ba were added to the samples of dried sediment (0.3 g), and then the sediment was digested in concentrated HF and $HClO_4$. After acid leaching ^{210}Po was spontaneously deposited for 4 h on a silver disc, which was then placed in α-counter for 24 h. Unsupported ^{210}Pb was determined on the basis of the distribution of total ^{210}Pb by subtracting the values

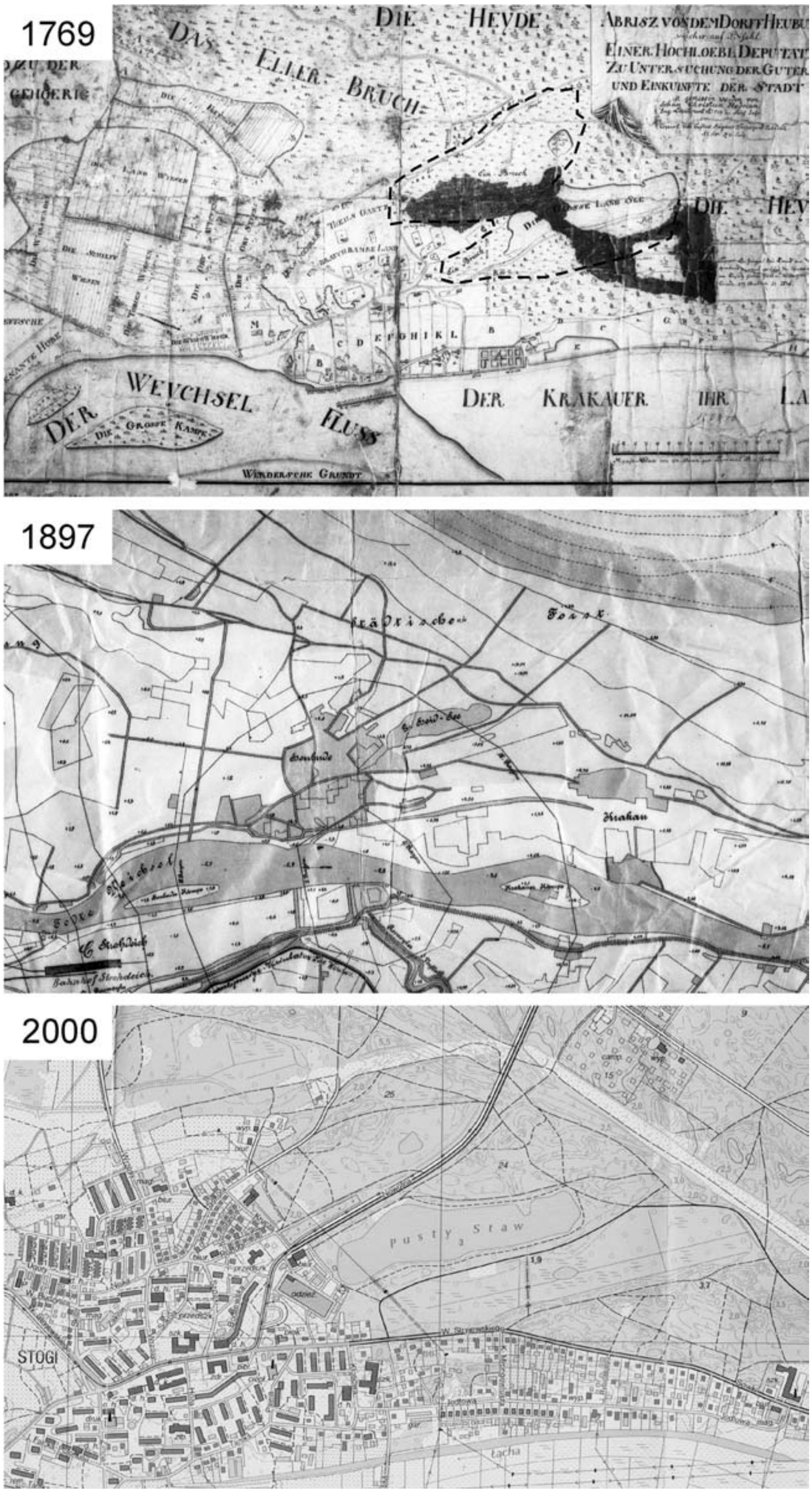

Figure 2. (a) Situation near Pusty Staw in the second half of the 18th century (Hadrian 1769). Dotted line marks the deforested area visible on the map. (b) Map of the surroundings of Pusty Staw from the end of 19th century (Block 1897). (c) Present surroundings of Lake Pusty Staw (Główny Urząd Geodezji i Kartografii 2000). Archival maps from the collection of the Provincial State Archive in Gdańsk.

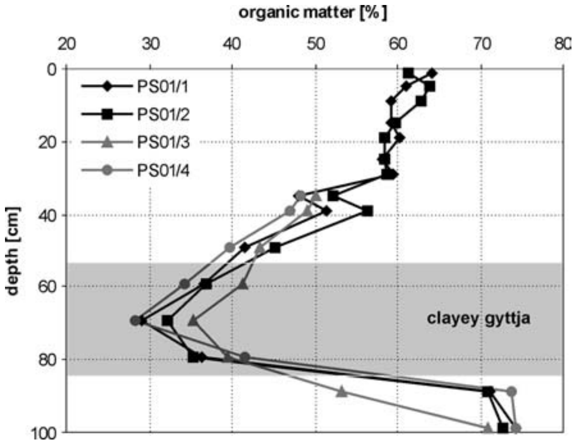

Figure 3. Comparison of the organic matter content in the cored sediments.

obtained in lower segments of the cores regarded as supported ^{210}Pb. In order to calculate the age of sediments and sedimentation rate, a CRS model was used, which is relatively resistant to disturbances in the core and, in a vast majority of cases, gives good results (Appleby 2001).

^{137}Cs activity was determined by gamma spectrometry. After drying, the sediment was ground in an agate mortar to provide homogeneity. Samples of known mass were placed in a gamma counter equipped with HPGe detector of energetic resolution 1.8 kV for line Co-60. Calibration of the counter was performed on the basis of reference International Atomic Energy Agency materials (SOIL-6, IAEA-300). Mean counting time was 24 h.

In order to determine the main components of the sediment, the LOI procedure was used according to guidelines given by Bengtsson and Enell (1986). Methodological aspects of the use of LOI were presented in detail by Boyle (2004) and Heiri et al. (2001). Water content was determined by drying the material at a temperature 105 °C to constant weight. Organic matter and carbonate content were determined by burning samples at 550 °C for 2 h followed by combustion at 925 °C for 4 h, respectively. The remaining part of the sediment was identified as siliciclastic material. The particle size distribution was determined with a laser counter Analysette 22 (Fritsch) after removal of organic matter (30% H_2O_2), according to methodology presented by Agrawal et al. (1991). Determinations of the chemical composition elements were performed at the Department of Marine Chemistry and Biochemistry IO PAS in Sopot. Sediment samples (0.5 g) were transported to teflon vessels and the wet digestion was performed in a mixture of HF and $HClO_4$. The element concentrations (Ca, Mg, Na, K, Al, Fe, Mn, Cu, Zn, Cd and Pb) were determined with a Thermo Jarrel Ash spectrometer Video 11E (Anonymous 1995).

Results

Core lithology

The cored sediments reveal a diversity both in terms of macroscopic features as well as particle size distribution (Figure 4). Distinct in colour and consistency, a zone of clayey gyttja was observed in all the cores at the depth of about 55–85 cm. Thus, three distinct units may be distinguished in the analysed core. In the basal zone, the sediment is composed of homogenous dark brown fine detritus gyttja. Fraction 4–63 μm, making up about 70% of the sediment mass, clearly dominates in the particle size distribution. The remaining 30% is made up of finer fractions. No material coarser than 63 μm was observed. Above this, there is lighter brownish-grey clayey gyttja with slightly less water content. The proportion of clayey (<2 μm) and silty (2–4 μm) fraction increases in this layer. The surface sequence is a homogenous, brownish-black, fine detritus gyttja of very high water content (90–95%). Fraction 4–63 μm dominates constituting over 80% of the sediment mass.

Chronology

In order to determine the chronology of the analysed core the ^{210} Pb–^{137}Cs method, as well as changes in the lithological features of the sediment were used. The distribution of unsupported ^{210}Pb shows some irregularities in the uniform activity in the surface layer (Figure 5). Such a distribution, slightly departing from a classic one, is often observed and described in the literature (Jones and Bowser 1978; Sharma et al. 1987; Appleby 1998). It is usually explained in one of two ways: as an effect of an acceleration in sedimentation rate in surface layers, or as evidence of sediment mixing caused by waves and bioturbation. The small depth of the lake does not provide stable conditions for sedimentation, and good oxygen

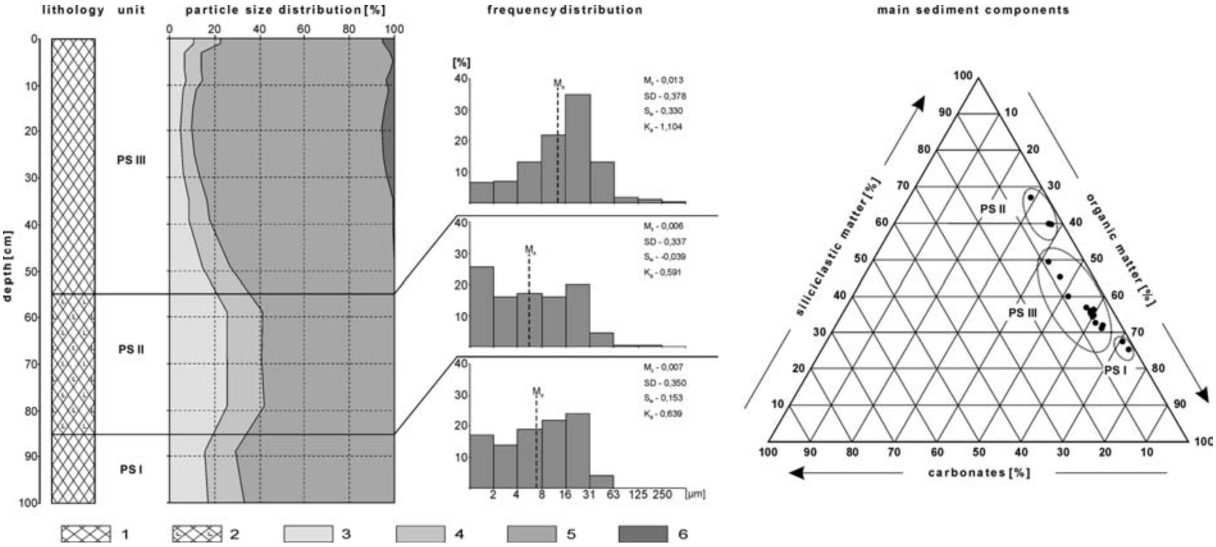

Figure 4. Lithology, particle size distribution and main components of sediments. (1) – fine detritus gyttja, (2) – clayey gyttja, (3) – fraction < 2 μm, (4) – fraction 2–4 μm, (5) – fraction 4–63 μm, (6) – fraction > 63 μm, M_z – mean diameter (mm), SD – standard deviation, S_{ki} – skewness, K_g – kurtosis.

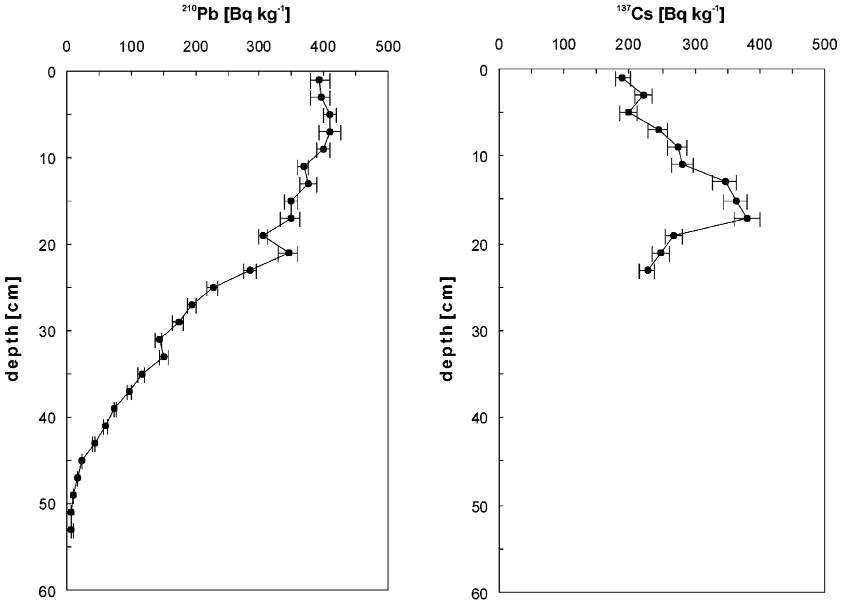

Figure 5. Distribution of unsupported ^{210}Pb and ^{137}Cs.

conditions are favourable for intense activity of benthos organisms. The uniform profile of ^{210}Pb in the surface layer of sediment suggests a possibility of mixing up to the depth of about 10 cm. As the distribution of ^{137}Cs reveals a clear maximum at the level 13–17 cm, forming a peak which can be a chronological marker, it does not seem possible that the mixing of sediments would totally disturb the stratigraphy of the sediment (Appleby 1998). Due to its considerable range of activity, the distribution of ^{210}Pb gives grounds for obtaining a reliable time scale.

Calculated maximum age of sediments was 181 years at the level of 53 cm (Figure 6). The

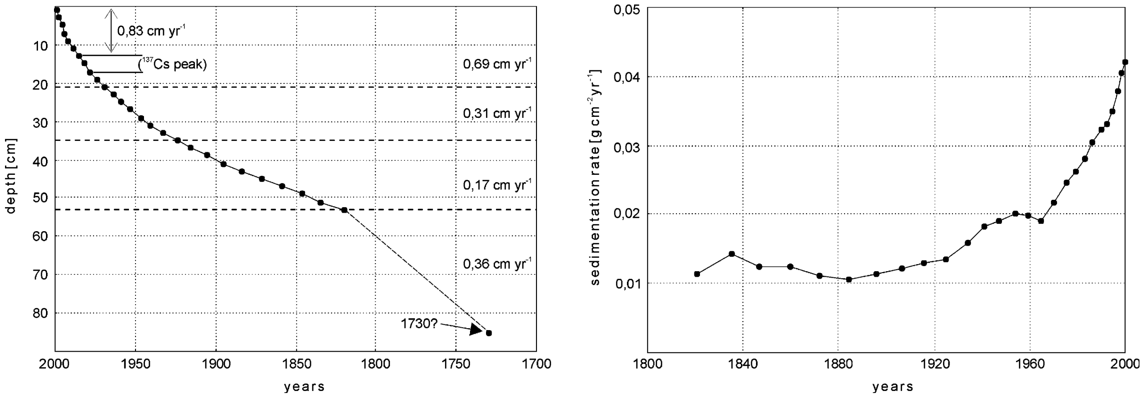

Figure 6. Age of sediments and sedimentation rate.

time scale determined using ^{210}Pb is well matched by the peak of ^{137}Cs. The extrapolation to the year 1730AD made on the basis of the clayey gyttja unit fits well with the curve of sediment age. The formation of such a distinct unit must have been caused by a significant change in the conditions of the catchment. In light of the analysis of historical materials it is likely that the cause was the deforestation of a part of the catchment in the first half of the 18th century. A return to detritus gyttja sedimentation occurred after the afforestation at the beginning of the 19th century. The upper boundary of the clayey gyttja unit at depth 55 cm is about 190 years old, which corresponds with the period of the completion of afforestation works in the catchment. Using 1730–1810AD for the upper and lower boundary of this unit, sedimentation rate would be 0.36 cm year^{-1}. Although this causes a considerable bend of the curve of sediment age, it is justified by the changes in the catchment. The intensity of erosion in the catchment partially devoid of forest cover was certainly significantly higher.

The verification of the radiometric dating with the changes of lithology justifies the statement that the mixing of surface sediments, which must have certainly taken place, did not considerably influence the reliability of the obtained time scale.

Geochemistry

Geochemical features of the sediments correspond well with the core lithology confirming the division into three units (Figure 7). In the first unit (PS I), the distinctive organic matter content exceeds 70%. The remaining part of the sediment is formed of siliciclastic material; the content of carbonates does not exceed 2%. Unit PS II (85–55 cm) contains much smaller amounts of organic matter ($<40\%$) and the carbonate content is also small; the main component of the sediment is siliciclastic material. Unit PS III (0–55 cm) is characterised by organic matter content between 40 and 65%, siliciclastic material from 30 to 50% and carbonates below 10%.

Similar variability of elements usually related to the processes of chemical and mechanical denudation in the catchment (Mg, K, Al) is characteristic of the distribution of chemical elements in the study cores (Figure 7). In all cases, Mg, K and Al maxima occur at level 60–90 cm. The sodium profile is slightly more irregular and does not show any relation to the lithology. Considerably different is the calcium profile, with a clear maximum at level 30–50 cm. Calcium is an element which very easily migrate in solutions, however, it cannot be related directly to the acceleration of erosion in the catchment due to its interactions with organic elements, especially humic and fulvic acids (Engstrom and Wright 1984). Thus, the interpretation of changes in Ca is often difficult.

Iron clearly increases in the basal zone of the core up to 70 cm. Then a slight decrease can be observed followed by another increase at level 15–30 cm. Completely different is the distribution of Mn, with a clear peak at 40–60 cm reaching several times higher than in the case of the remaining samples of sediments.

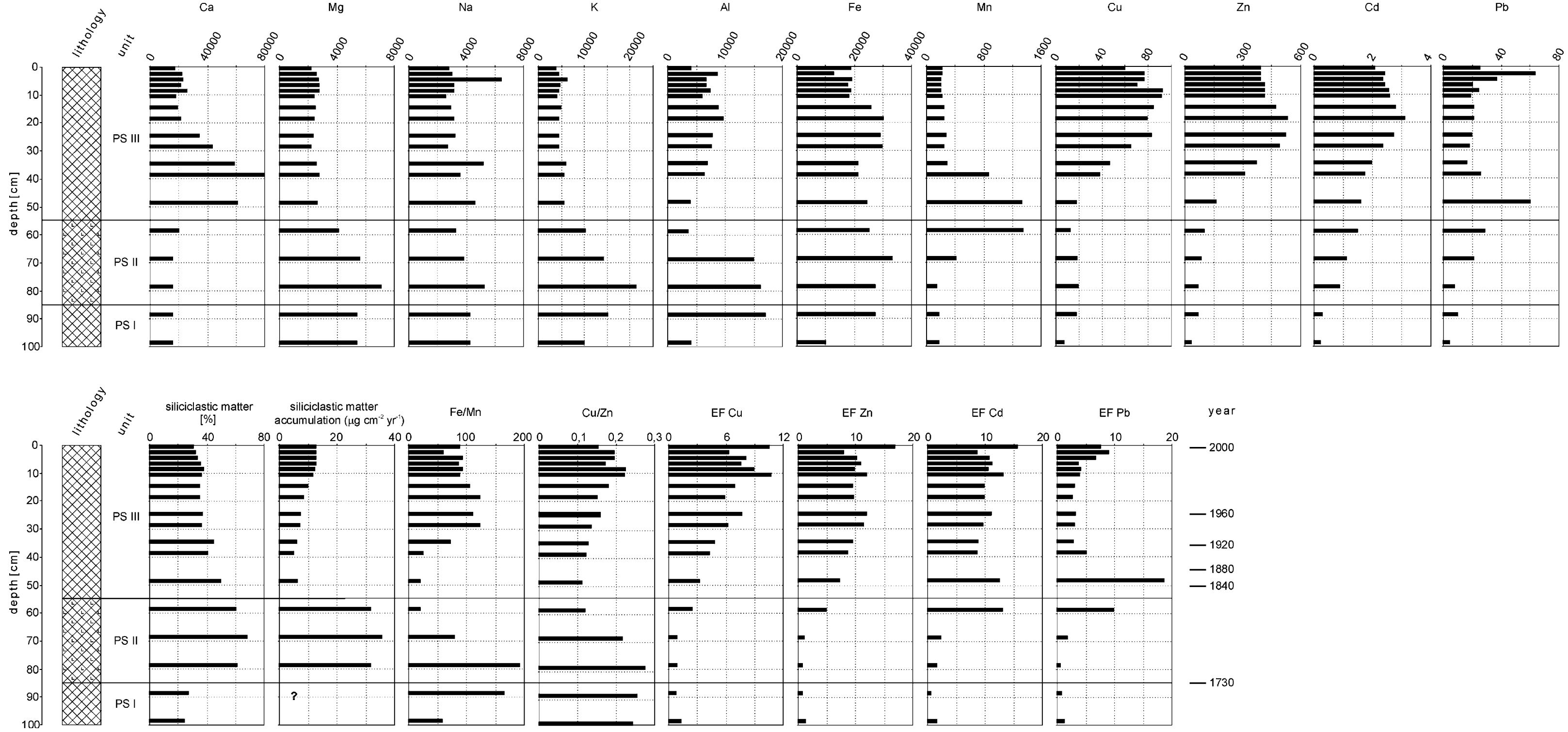

Figure 7. The records of selected elements in recent sediments of Lake Pusty Staw. Concentrations in upper series of profiles given in ppm.

Heavy metals in the sediments of Pusty Staw have, except for lead, a very similar pattern. In lower segments of the core, the concentrations are stable but there is an increase upwards. In the case of cadmium this increase is occurring from 80 cm, while of copper and zinc from 40 cm. The elements reach their highest values at 10–30 cm, corresponding to the second half of the 20th century. There is a small decrease in concentrations in the surface layer. In the distribution of lead an increase from 70 cm with a clear maximum at 50 cm was observed. A second maximum occurs in the surface layer.

Heavy metals originate not only from anthropogenic sources but may be supplied to the lake by the natural flux of elements from the catchment. One of the ways to distinguish the fraction of metals related directly to man's influence is by normalisation with respect to Al (Kemp et al. 1976; Van Metre and Callender 1997). The variability of those normalised concentrations is presented in the form of an enrichment factor (EF), which is a ratio of the content of the element in the analysed layer to the content corresponding to the preindustrial period:

$$EF = (C_X/C_{Al})_S/(C_X/C_{Al})_C, \quad (1)$$

where

$(C_x/C_{Al})_s$ – ratio of concentration of element x and aluminium in the sample;

$(C_x/C_{Al})_c$ – ratio of concentration of element x and aluminium in unpolluted sediments.

It appears that this is a measure better expressing the increase in the content of metals than the absolute values. As a reference level with respect to which the enrichment was calculated, the mean concentration of level 90–100 cm, corresponding to the period before 1730AD was assumed. Such an approach also revealed a considerable increase in heavy metals content (Figure 7), which confirms the anthropogenic character of this tendency. A very similar pattern occurs in the Cu and Zn, whose small increases can be observed from the beginning of the 19th century, and a more significant one about 1920AD. The distribution of EF values for cadmium in the 20th century is similar, except in the earlier period values are higher than those of copper and zinc. In contrast, distribution of EF for lead is completely different. An increase occurs already in the beginning of the 19th century with a maximum in the second half of this century, then the values fall rapidly and stabilise. Another rise occurs in the uppermost sequence of the core at the end of the 20th century.

Table 1. Heavy metals flux in sediments of Lake Pusty Staw.

Depth (cm)	Age	Cu	Zn	Cd	Pb
		(μg cm^{-2} yr^{-1})			
2	2000	0.76	4.97	0.026	0.32
4	1999	0.97	4.97	0.031	0.80
6	1997	0.96	4.94	0.030	0.47
8	1995	0.87	5.11	0.030	0.25
10	1992	1.14	5.07	0.031	0.30
12	1990	1.06	4.77	0.030	0.22
16	1983	0.82	4.59	0.027	0.21
20	1975	0.68	4.55	0.027	0.18
26	1959	0.60	3.79	0.020	0.14
30	1947	0.45	3.39	0.016	0.12
36	1925	0.28	2.26	0.012	0.10
40	1907	0.18	1.52	0.009	0.13
50	1847	0.11	1.00	0.010	0.37

An additional component of anthropogenic heavy metals enrichment of the sediments is metal flux (F). This parameter was calculated according to the following formula (Vesely et al. 1993):

$$F = R \times (1 - \phi) \times p \times MM \times C, \quad (2)$$

where

R – sedimentation rate (cm/year);

ϕ - sediment porosity;

p – dry sediment density (g/cm^3);

MM – siliciclastic material content (%);

C – concentration of metal in sample (μg/g).

The calculated F values in the sediments of Pusty Staw (Table 1) increase systematically from the base of the core reaching the highest level in the beginning if the last decade of the 20th century. In the case of Cu and Zn, a continuous rise beginning in the mid-19th century is observed, while cadmium increases only from the mid-20th century. The pattern of lead flux is more complicated with a high value in the mid-19th century, a decrease in the beginning of the 20th century and a slow rise from the 1960s. In the case of all the metals, the increasing tendency is reversed in the surface layer of sediments.

Discussion

The analysed sediments represent the most recent 300 years of history of Lake Pusty Staw. During this period, the anthropogenic pressure was increasing, manifested initially in changes in terrestrial vegetation caused by the burning of forests and afforestation and later by a systematic progress in tourist and industrial development. This brought about considerable changes in lithological type and geochemistry of sediments. On this basis, reconstruction of the influence of man's activity on the course of the erosion processes in the catchment and progressing pollution of the lake was possible.

Erosion

Significant changes in the catchment (burning forests due to warfare in 1733–1734) resulted in intensification of erosion processes and an almost immediate response in sediment. According to Einsele and Hinderer (1997), the intensity of erosion can increase several times, though there are known cases of an increase of several hundred times. The sedimentation rate increased in Lake Pusty Staw (Figure 6) and a unit of clayey gyttja (PS II) with high content of siliciclastic material was deposited. Similar consequences of erosion in the catchment and acceleration of sedimentation rate were recorded in many lakes of Great Britain and Ireland (Edwards and Whittington 2001). The change of lithological type of the sediment (from organic, detritus gyttja to clayey gyttja) is also a logical consequence of the accelerated erosion (Dearing 1991). The increased supply of siliciclastic material from the catchment to the lake is confirmed by the estimated sedimentation rate during this period, which was three times higher than in the later period (Figure 7).

Changes in the intensity of erosion in the catchment are usually accompanied by an increase of elements, such as Mg, Na, K or Fe (Engstrom and Wright 1984; Dearing and Foster 1993; Boyle 2001). In Lake Pusty Staw this was observed in the case of magnesium, potassium and iron, whose concentrations are high in this unit. However, there is no similar tendency in the case of sodium. Similar discrepancies between the tendency of sodium and potassium have been recorded before, e.g., in Lake Gościąż (Goslar 1998).

A considerable increase in the sedimentation rate in the first and especially the second half of the 20th century is also observed. This can be partially caused by increasing lake productivity and receiving sewage from the new haberdashery plant. It does not seem reasonable that erosion is responsible for such a distinct increase because no significant changes in land use were known. Accelerated sedimentation rate is supported by the good match of the location of ^{137}Cs peak with ^{210}Pb dates. However, there remains the problem of sediment mixing and the possible influence on calculated sedimentation rates. Abril (2003) questioned the use of distinct ^{137}Cs peaks as a definitive demonstration of acceleration and stated that incomplete mixing of surficial sediments can explain the ^{137}Ce peak and the flattening of the ^{210}Pb profile. In such a case, sedimentation rates in the uppermost part of the core calculated by the CRS model can be overestimated. The mean sedimentation rate values seem reasonable and do not differ from the results of research on other Polish lakes (Goslar et al. 1999; Tylmann and Białkowski 2002).

Changes in erosion intensity in the catchment also influence the redox conditions occurring in the lake. One of the frequently used indices allowing a reconstruction of changes in redox conditions during the deposition of the sediment is the ratio of iron and manganese (Digerfeldt 1972; Engstrom and Wright 1984; Boyle 2001). High values of the Fe/Mn ratio, especially if they are related to higher concentrations of iron itself, may potentially indicate reducing conditions during deposition of the sediment. However, it should be emphasized that the interpretation of this index in the low stability environment of recent bottom sediments must be very careful due to the high mobility of both iron and manganese (Engstrom and Wright 1984; Boyle 2001). In the vast majority of lakes, only the surface layer of sediment is characterised by oxidising conditions and at a depth of several centimetres reducing conditions usually occur (Boyle 2001). This is mostly caused by oxygen depletion due to the activity of benthos organisms. Thus, iron and manganese become much more mobile, which, as a result of diffusion, may lead to the formation of distributions poorly reflecting the actual changes in conditions of sediments deposition. In the Lake Pusty Staw sediments, a high variability of this ratio was recorded, with the highest values in lower sequences of the core. Minimum values at 40–60 cm are caused by high concentrations of Mn. In palaeolimnological research the Cu/Zn ratio is sometimes also used as an indicator of redox conditions (Vuorinen 1978; Goslar 1998). The usefulness of this indicator results from the fact that in strongly reducing conditions characterised by the presence of H_2S, copper precipitates faster than zinc. Thus, higher values of Cu/Zn can indicate reducing conditions. In Lake Pusty Staw the distribution of this ratio reveals a high conformity with the distribution of Fe/Mn ($R = 0.60$). However, due to difficulties in the interpretation of such indices, a more detailed analysis of changes in the trophic status of the lake requires a confrontation with results of palynological analyses.

Pollution

Anthropogenic pollution of the natural environment has a much longer history than the last several hundred years (Weiss et al. 1999; Bränvall et al. 2001; Smol 2002). Yet, without doubt, this period brought about the greatest increase of pollution both on global and local scale. One of the most often used indicators of environment pollution is the concentration of heavy metals in sediments (El-Daoushy 1986; Norton 1986; Renberg 1986; Norton et al. 1992). The concentrations obtained in sediments of Pusty Staw, in the light of earlier studies concerning lakes in industrial areas (Charlesworth and Foster 1993; Aström and Nylund 2000), are not especially high. However, normalisation with respect to Al and expressing the variability of concentrations in the form of an EF reveals significant trends for all the analysed heavy metals. Enrichment of several times is observed most often in literature, however, enrichment of even several hundred times is sometimes recorded (Müller et al. 2000). However, usually so high enrichment is related to mining industry, while in the case of Gdańsk, an increase of over 10 times in the concentration of heavy metals in sediments should certainly be seen as significant.

The increase of the content of copper and zinc in the beginning of the 20th century can be attributed to the establishment of the haberdashery plant, which probably discharged the sewage directly into the lake. A systematic increase in pollution with the maximum between 1960 and 1990 was found. The surface maximum should be interpreted with caution due to the active character of the surface layer, biogeochemical processes and diagenesis occurring in it (Santschi et al. 1990; Callender 2000). The near-surface maximum is a phenomenon which is sometimes observed (Kemp et al. 1976; Boyle 2001) and can be attributed to the diffusion of metals and processes of exchange between the sediment and near-bottom water. The difficulties in interpreting metals concentration within mixing zone increase due to bioturbation which can substantially influence metal distribution (Boudreau 1999). Thus, high EF values in the surface layer should not be necessarily viewed as an effect of increased human pressure.

It is difficult to interpret directly the cadmium and lead distributions in the 19th century. There are at least several facts informing about the human activity in the catchment of Pusty Staw during that period. Throughout the century, the health resort on the western shore of the lake was developed. Another influence could have been exerted by warfare at the beginning of the 19th century. High concentrations of lead in sediments, whose age is about 150 years should be attributed to pollution of typically local character, probably connected with the functioning of the health resort.

The measure of supply of heavy metals into the lake in individual periods is referred to metal flux. This method is often used in research on anthropogenic influences (Vesely et al. 1993; Boyle et al. 1998; Alvisi and Dinelli 2002), though the need for caution is emphasised by Engstrom and Wright (1984). Relating concentrations to sedimentation rate theoretically gives actual values of metal flux, however this parameter is very sensitive to errors resulting from changes in sedimentation rate. In fact, it seems likely that the high values of metal flux after 1990 are not a reflection of the actual level of pollution, as human pressure was certainly smaller during that period due to economic crisis and increasingly more widespread respecting the norms of pollutants emission.

Conclusions

The analysed bottom sediments of Lake Pusty Staw represent a period of considerable human influence covering about 300 years. Initially, this was manifested in changes of vegetation cover in the catchment, leading to changes in the intensity of erosion and trophic status of the lake. The burning of forests resulted in a large increase in erosion intensity, clearly reflected in sediments. The development of tourism as well as warfare caused considerable pollution of the lake waters from the beginning of the 19th century. Pollution was rising systematically due to industrialisation during the 20th century.

The unambiguous character of the investigated changes in sediments form a clear record of anthropogenic changes and confirms that sediments of small and shallow lakes are a very valuable archive of information about transformations of the natural environment, especially on a local scale.

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