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Surface sediment composition in an inundated opencast sulphur mine (Piaseczno reservoir, Southern Poland)

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Abstract

The chemical characteristics of the surface sediment (0–5 cm) in a lake which formed in an opencast sulphur mine in Southern Poland have been analysed. Generally, the concentration of major elements (N, P, S, Ca, K, Mg, Cl, Fe, Si, and Al) and trace elements (Ag, As, Ba, Cd, Co, Cr, Cu, Ga, Hg, I, Mn, Mo, Ni, Pb, Rb, Sr, Ti, Y, and Zn) in the lake sediment reflected the natural regional background. The sediment was characterised by low amounts of organic matter (LOI ca. 5%). MANOVA indicated that the concentrations of 60% of the elements differed significantly between transects and 32% with respect to depths, whereas seasonal differentiations were not found. The relationships between the studied elements calculated using factor analysis and correlation matrix are discussed. The bottom sediment show considerable heterogeneity, which is probably connected to their allochthonous origins and the young age of the lake.

Introduction

The number and importance of post-exploitation areas has increased during recent decades in many countries. The primary goal of 'post-mining' activities is to eliminate ecologically negative consequences of the extractive industry (Puchalski 1985). Artificial lakes have been created in places where there were opencast mines e.g. lignite mines (Abel et al. 2000; Bell and Weithoff 2003; Dumnicka and Krodkiewska 2003), abandoned granite (Ejsmond-Karabin 1995) or limestone quarries (Ivanoff 1998; Galas 2003). The hydrochemical properties of their waters are mainly determined by their regional geochemical background.

There have been only a few studies on the artificial lakes formed in inundated opencast sulphur mines (Zozula and Gaydin 2000; Żurek 2002). One such lake is located in the region with the largest deposits of sulphur ore, in Southern Poland. It was formed to replace the first opencast mine 'Piaseczno', where sulphur was extracted from 1960–1971 (Krajewski 1995). Complex hydrochemical and hydrobiological studies on Piaseczno reservoir have been carried out in 2000–2003. The aim of our investigation was to determine the concentration of both major and trace elements in the sediment during different seasons, at different depths and transects of the sediment.

Study area

Piaseczno reservoir is situated in the Tarnobrzeg sulphur region (21° 35′E, 50° 35′N). It has a surface area of 63 ha, maximum water volume is

3.5×10^6 m^3 and maximum depth 21 m (Figure 1). The lake, formed by natural filling of the opencast pit with highly mineralised waters from Quaternary and Tertiary aquifer, is meromictic and stratifies in summer with a thermocline between 2.5 and 5 m. The lake water had a neutral pH and was strongly mineralised, with electrolytical conductivity (EC) ranging from 1034 to 16400 μS cm^{-1}, very hard (510–1605 mg of $CaCO_3$ l^{-1}), and high in Cl^- (especially in the near-bottom water) and SO_4^{2-} ions (200–5000 and 300–1000 mg l^{-1}, respectively) (Żurek 2002; Żurek 2006). The lake is situated ca. 20 km from the nearest town; there is no agriculture or roads nearby.

Catchment geology

A geological cross section of deposits in the Piaseczno area reveals that it is composed of: Holocene and Pleistocene mud, sands and gravel, the Sarmatian clayey deposits, sulphur-bearing limestone, gypsum, the Baranów sands, brown-coal clays, the carboniferous siltstone and claystone (Figure 2) (Pawłowski et al. 1965). The sulphur-bearing limestone is composed of calcite and sulphur, which makes up to 94% of the rock, while gypsum, quartz, aluminium and iron oxides, titan, and strontium sulphates are admixtures. The Sarmatian clayey deposits form a blanket over 80% of the sulphur mine. The maximal thickness of this clay layer is a dozen meters. It is covered by top soil and an under soil layer which is 10–15 m thick and is formed of the Holocene and Pleistocene mud, sands and gravel (Krajewski 1995).

Materials and methods

The sediment samples were taken in different seasons (3.04.2001, 18.07.2001, 6.11.2001, 15.01.2002) from three transects (Figure 1). On each transect sediment samples were collected from three water depths: 1, 5 and 10 m (in total 36 samples). Studied transects differed in the abundance of emergent macrophytes, the degree of shelter from the wind

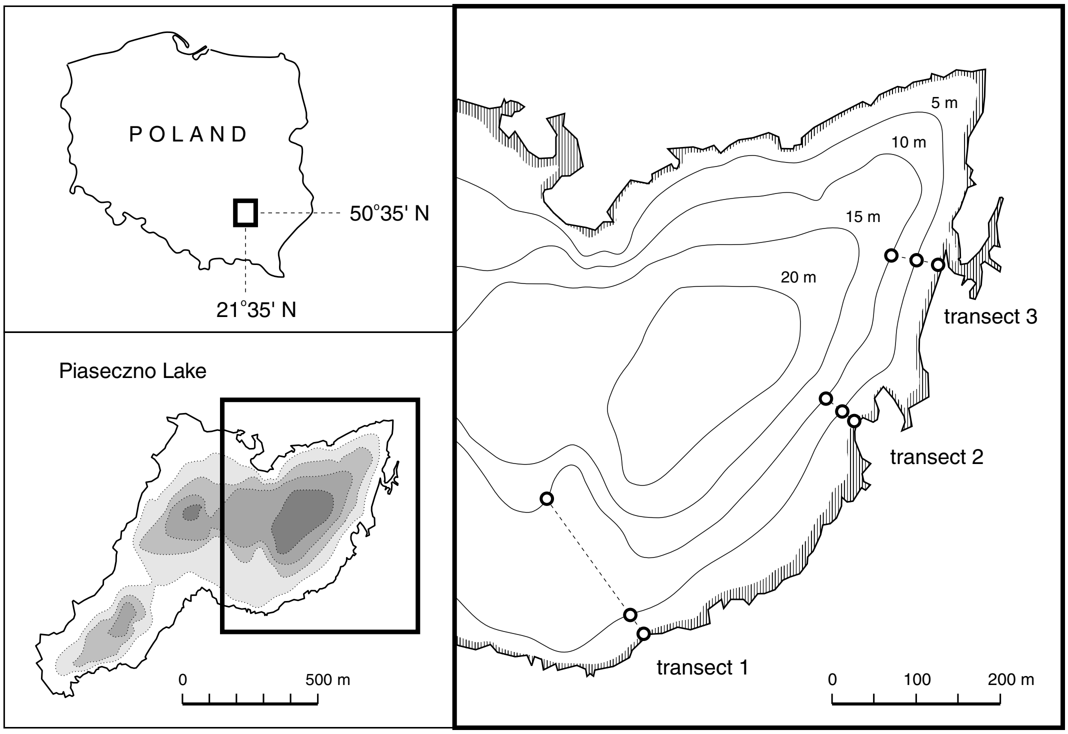

Figure 1. Map of the study area (Piaseczno reservoir) with the transect locations indicated. Vertical hatching indicates distribution of emergent macrophytes.

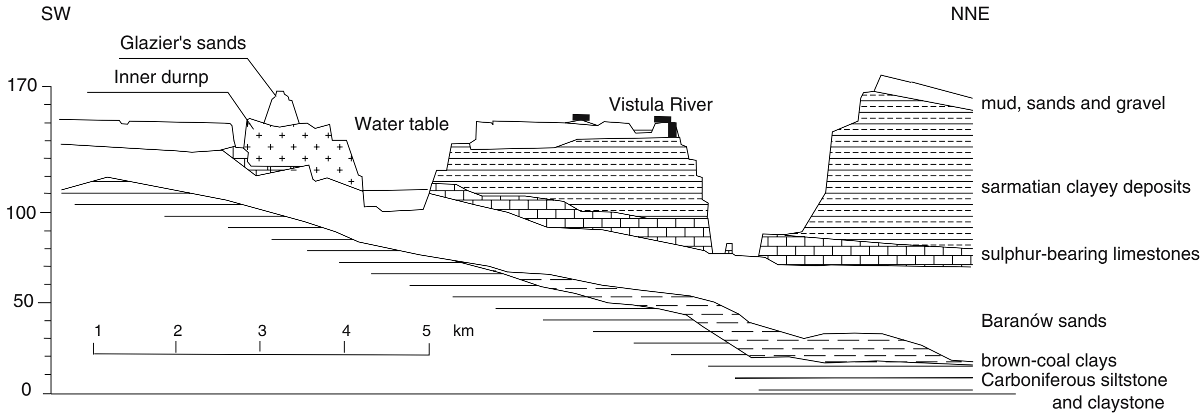

Figure 2. Geological cross section of deposits in the Piaseczno area (according to Żurek 2002).

and slope of the lake basin. Macrophytes were present only on transects 2 and 3 both of which were situated in a protected part of the lake and therefore not exposed to wave action, in contrast to transect 1. Here, exposure to wave action, and with a forested shore reducing soil erosion, resulted in a thinner layer of sediment than on transects 2 and 3, while more stones and gravel were found at transect 1. Very steep slopes at transects 2 and 3 (compared to transect 1) resulted from the excavation of sulphur-bearing limestone.

Samples of the upper sediment (0–5 cm) layer were collected using a polyethylene corer with an area of 12.56 cm^2, one sediment sample contained several subsamples. For each sample, total major and trace elements, and organic matter content were determined. In the spring samples grain size was also measured.

To establish the local geochemical background, three types of rock: sulphur-bearing limestone, Sarmatian clayey deposits, and Baranów sands were collected from the drainage area.

Analytical methods

The samples of sediment or rock were dried at 105°C for 24 h. Samples used for total nitrogen and phosphorus determinations were then homogenised using a planetary mill 'Pulverisette 5' with teflon grinding balls. Total nitrogen was determined by the Kjeldahl method and total phosphorus using a spectrophotometeric method with ammonium molybdate and ascorbic acid as a reducing agent (APHA 1992). Organic matter content was estimated by loss on ignition (LOI) at 550 °C for 2 h.

The samples used to determine total concentrations of Mg, Al, Si, S, Cl, Fe, Mn, K, Ca, Ti, V, Cr, Ni, Cu, Zn, As, Br, Rb, Sr, Y, and Pb were prepared by grinding a mixture of 3 g of the material and 0.3 g of paraffin (Merck Hoechst wax C micropowder) in a planetary mill (Pulverisette 7 Fritsch) at 500 rpm for 5 min. Then 2.7 g of the powder was used for preparation of tablets (31 mm in diameter) in a pallet die (Graseby-Specac). The tablets were produced by application of a pressure of 25 t for about 5 s.

The measurements were made using an energy-dispersive X-ray spectrometer (EDS 2000, Oxford Instruments, UK) under vacuum. This spectrometer is equipped with a silver anode X-ray tube and had an Si (Li) detector (area 30 mm^2, thickness 3 mm) with an 8 μm thick beryllium window (FWHM at 5.9 keV = 145 eV). Three sets of working conditions were applied depending on the elements to be measured: (1) tube voltage 5 kV, current 300 μA (without filter), lifetime 240 s for Mg, Al, Si, P, S, Cl, K, and Ca; (2) tube voltage 40 kV, current 20 μA (thin Ag filter in front of the tube), lifetime 360 s for Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, As, Br, Rb, Sr, Y, and Pb; (3) tube voltage 45 kV, current 50 μA (Cu filter in front of the tube), lifetime 360 s for I and Ba. The detection limits ranged from 300–50 ppm for light elements ($Z = 12 - 20$) to 2 ppm for heavy elements ($Z > 20$). Namely, detection limits in sediment samples were 300 ppm for Na, 100 ppm for Al, Mg and Si, and 50 ppm for P, S, Cl and Ca. For heavier elements, i.e. those with atomic numbers higher than 20 (Ti–U), detection limit was about 2 ppm. The calculations of elemental concentrations were based on standard sediment IAEA-SL1 and IAEA-SL3 from the International Atomic Energy Agency.

Grain fractions were determined using the aerometric method. The fractions determined were: sand (1.0–0.05 mm), clay silty (0.05–0.002 mm), and clay (< 0.002 mm).

Statistics

In order to verify the level of trace elements in the sediment the enrichment factors (EF) were calculated according to the formula (Förstner 1989):

$$\mathrm{EF} = \frac{[\mathrm{Me}]_s[\mathrm{Al}]_s}{[\mathrm{Me}]_b[\mathrm{Al}]_b}$$

where $[\mathrm{Me}]_s$ is the sediment metal concentration; $[\mathrm{Al}]_s$ the level of Al in the sediment; $[\mathrm{Me}]_b$ the metal base level (background); $[\mathrm{Al}]_b$ is the Al base level. Al was used as a geochemical normaliser. As a background, the concentrations of elements in the rocks from the catchment area (regional baseline level) were used.

MANOVA was used to establish the difference in element concentrations between lake depths, transects, and seasons. The relationships between the major elements were studied using factor analysis, whereas between all studied elements using correlation coefficient.

Results

Catchment basin rocks and sediments

Concentrations of major and trace elements in the rocks of the catchment area and in the littoral zone sediment of Lake Piaseczno are shown in Tables 1 and 2. In the reference rocks the following major elements dominated: Si, S, Al, Ca, Fe, Mg, and K (Table 1). Among trace metals the highest concentrations in reference rocks were found for Ba, Sr, and I, while the lowest value were found for Pb, Cu, Ni, Ga, and Ti (Table 2).

In the bottom sediment of Piaseczno lake the following major elements dominated: silica (average 46.4%), sulphur (7.6%), calcium (5.6%), aluminium (4%), iron (2.4%), potassium (1.3%), and magnesium (1.1%) (Table 1). Among trace elements in Piaseczno sediment in the highest concentration occurred for Ba and Sr, while in the lowest one for Ti, Ga, Pb (Table 2). The values of EF calculated for trace elements of Piaseczno lake sediment are presented in Table 3. The values of EF-1 (calculated for clay rocks) for most of the trace elements (except Ti, Mn, and Fe) ranged from 1.2 to 15.6, whereas the values of EF-2 (for carbonate rocks) and EF-3 (for sands) of these elements were usually less than 1. This indicated that the elements derived from various source rocks during weathering, and that natural physical and geochemical processes control their distribution in the sediment.

The bottom sediment (except at 1 m depth on transect 1) were characterised by a high percentage of the clay silty fraction (63–65% in transect 1,

Table 1. Chemical composition (expressed as %) of sediment ($N = 36$) and rock ($N = 3$) of Piaseczno reservoir, Poland.

Lake sediments:	LOI	N-tot	P-tot	S-tot	Ca	K	Mg	Cl	Fe	Mn	Si	Al
Mean	5.0	0.040	0.006	7.6	5.6	1.3	1.1	0.7	2.4	0.5	46.4	4
Minimum	1.6	0.002	0.002	2.5	2.4	0.8	0.5	0.3	1.2	0.1	22.5	2.4
Maximum	12.6	0.130	0.011	45.8	13.5	1.6	1.5	1.4	7.9	2.6	59.6	5.5
Mediana	3.8	0.029	0.006	4.5	5.0	1.4	1.1	0.6	2.2	0.3	48.1	4.2
SD	3.0	0.030	0.001	8.6	2.3	0.2	0.2	0.3	1.1	0.6	9.0	0.8
Reference rocks												
Clay deposits			0.007	6.1	2.6	1.5	1.6	0.8	1.7	0.040	60.7	5.1
Baranów sands			0.002	0.7	0.1	0.4	0.5	0.0	0.2	0.010	89.8	1.7
Sulphur-bearing limestones			0.003	59.1	6.4	0.1	0.1	0.3	0.0	0.003	1.7	0.3
Shales[a]			0.07	0.24	2.21	2.66	1.5	0.020	4.72	0.085	7.3	8
Sandstone[a]			0.02	0.024	3.91	1.07	0.7	0.001	0.98	0.002	36.8	2.5
Carbonate[a]			0.04	0.12	30.23	0.27	4.7	0.015	0.38	0.11	2.4	0.42

[a] According to Turiekian and Wedepohl (1961).

Table 2. Chemical composition (expressed as $\mu g\ g^{-1}$) of sediment ($N = 36$) and rock ($N = 3$) of Lake Piaseczno, Poland.

Lake sediments:	Pb	Cu	Zn	Cr	Ni	Sr	Mo	Rb	Ba	Ga	Y	Ti	I
Mean	23.4	43.8	72.0	113.0	32.3	453.5	76.8	64.3	554.4	14.6	65.3	4.8	178.3
Minimum	10.0	20.0	49.0	47.0	16.0	162.0	1.0	27.0	166.0	6.0	24.0	0.4	6.0
Maximum	44.0	62.0	106.0	284.0	67.0	3081.0	99.0	158.0	3116.0	30.0	89.0	13.1	1338.0
Mediana	22.0	44.5	71.0	92.5	30.5	268.0	80.5	67.0	386.0	14.0	67.5	4.5	100.0
SD	8.0	11.3	13.9	49.4	11.4	611.0	18.6	22.0	511.5	4.9	16.6	2.3	247.9
Reference rocks													
Clay deposits	34.0	25.8	19.3	43.7	35.3	134.7	24.3	34.2	92.3	33.8	25.5	48.7	139.0
Baranów sands	7	54	83	133	28	182	90	79	356	20	91	0.633	20.0
Sulphur-bearing limestones	22	31	25	54	7	42	178		104	9	82	0.116	24.0
Shales[a]	20	45	95	90	68	300	2.6	140	580	19	26	4600	2.2
Sandstone[a]	7	30	16	35	2	20	0.2	60	70	12	40	1500	1.7
Carbonate[a]	9	4	20	11	20	610	0.4	3	10	4	30	400	1.2

[a] According to Turiekian and Wedepohl 1961.

Table 3. EF calculated for the trace elements of Piaseczno reservoir sediment.

	Pb	Cu	Zn	Cr	Ni	Sr	Mo	Rb	Ba	Ga	Y	Ti	I
EF-1	0.9	2.2	4.8	3.3	1.2	4.3	4.0	2.4	7.7	0.5	3.3	0.1	1.6
EF-2	0.1	0.1	0.2	0.2	0.3	0.8	0.03		0.4	0.1	0.1	3.1	0.6
EF-4	1.4	0.3	0.4	0.4	0.5	1.1	0.4	0.3	0.7	0.3	0.3	3.2	3.8

For sediments $N = 36$, whereas for reference rocks $N = 3$. Calculated for regional: EF-1, clay rocks; EF-2, carbonate rocks; EF-3, Baranów sands.

62–85% in transect 2, and 71–93% in transect 3), and a low percentage of the clay fraction (1–5, 4–9%, 2–5%, respectively). Sediment from transect 1 contained higher amounts of sand-sized grains (depth 1 m – 77%) when compared to the other transects. Larger amounts of sand-sized grains were always observed at 1 m depth on each transect, but their proportion were diminished down vertical profile. No significant correlation was found between the elements studied and the grain fractions.

Organic matter values in the littoral sediment ranged between 1,6 and 12,6%, N-tot between 0,002 and 0,13% and P-tot between 0,002–0,011% (Table 1).

Statistics

In order to determine the spatial distribution of both major and trace elements, as well as the relationships between them, some statistical analysis were used.

MANOVA was used to determine the spatial distribution of major and trace elements with

Table 4. Significant differences (shown in bold) in the content of major and trace elements calculated for MANOVA between studied depths, transects, and seasons.

	LOI	Mg	Al	Si	S	Cl	K	Ca	Cr	Fe	Zn	Ga	Rb	Sr	Y	Mo	Ba	Pb
Depths																		
F	2.86	**3.51**	3.30	2.31	**5.89**	2.21	**4.87**	0.30	**5.51**	**3.72**	**4.71**	0.14	0.16	**5.51**	1.50	**4.17**	3.30	0.39
p	0.07	**0.04**	0.05	0.118	**0.007**	0.13	**0.015**	0.75	**0.01**	**0.037**	**0.017**	0.87	0.85	**0.01**	0.24	**0.03**	0.05	0.68
Transects																		
F	**3.97**	**10.6**	**15.85**	**6.30**	**3.46**	**7.11**	**25.53**	**6.40**	2.31	**5.55**	0.53	**10.00**	**8.60**	2.31	**15.27**	**3.67**	**5.36**	**6.74**
p	**0.03**	**0.0**	**0.00**	**0.006**	**0.045**	**0.003**	**0.0**	**0.005**	0.12	**0.009**	0.59	**0.001**	**0.001**	0.12	**0.00**	**0.04**	**0.01**	**0.004**
Seasons																		
F	0.30	0.64	1.22	0.04	0.54	0.59	1.50	0.94	0.91	0.65	0.45	2.46	1.96	0.91	0.41	0.73	0.60	0.36
p	0.82	0.60	0.32	0.99	0.66	0.63	0.24	0.43	0.45	0.59	0.72	0.08	0.14	0.45	0.75	0.54	0.62	0.78

The remaining elements did not show significant differences.

respect to the lake depths, transects, and seasons (Table 4). Thirty-two percentage of the elements were found to differ significantly between depths and 60% of the elements between transects, but statistical differences between seasons were not observed. In the case of Mg, S, K, Cr, Fe, Zn, Sr, and Mo concentrations, statistical differences were evident between different depths (Table 5). *T*-test indicated that samples from 10 m contained higher concentrations of these elements (except Mo and K) than samples taken from depths of 1 or 5 m. In general, the amounts of Al, K, Ga, Rb, and Y were lower in transect 1 than in transects 2 and 3 (Table 6). The inverse situation was found in the case of S, Cl, and Fe, which concentrations in the transects 1 were higher than in the transect 2 and 3 while amounts of LOI and Ca higher than in transect 3. Higher concentrations of Mg and Pb found in transect 3 differed statistically from the others.

To establish the relationship between the elements the factor analysis with raw varimax rotation (Figure 3) and correlation coefficients (Table 7) were used. Figure 3 showed that generally the elements are concentrated in two groups. The first group is represented by S, Cl, Ca, Fe, and organic matter whereas the second one by Si, K, Mg, and Al. Results presented above were confirmed by the correlation's matrix. Significant correlations were found between organic matter (LOI) and P, S, Cl, Ca, Fe, and I (Table 7). No correlations were found between trace elements and organic matter (except for I) or with Fe (except for Cr) and Mn, which determined trace element distribution in the sediment. Positive correlation between Fe and P, S, Cl and Cr was found. Si, K, Ga, Rb, Y, and Mo showed strong correlations with Al concentrations.

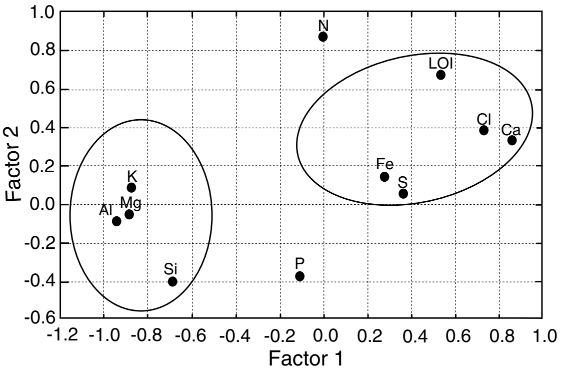

Figure 3. Two first factors of factor analysis calculated for 11 major elements from sediment of Piaseczno reservoir.

Discussion

In the catchment area of Piaseczno reservoir there are sulphur ore deposits. Therefore the geological structure of the rocks in the catchment area differs from the general distribution of major and trace elements in the Earth's crust as described by Turiekien and Wedepohl (1961). Among major elements concentrations of Ca, Al, Fe, K, and Mg occurring in the catchment basin rocks were similar, whereas those of S and Cl were much higher when compared to the average shale, carbonate

Table 5. Mean element concentrations ($N = 12$) and significant differences ($p < 0.05$, asterisk) between studied depths (1, 5, and 10 m; *t*-test) in Lake Piaseczno.

Depth (m)	Mg	S	K	Cr	Fe	Zn	Sr	Mo
1	1.1	4.4	1.3	88.3	1.8	62.7	261.5	84.8
5	1.1	4.9	1.4	105.8	2.4	77.8	279.1	79.3
10	0.9	13.5	1.2	145.1	2.9	75.4	997.5	66.2
1 and 5			*		*	*		
1 and 10		*		*	*	*	*	*
5 and 10	*	*	*				*	

Table 6. Mean element concentrations ($N = 12$) and significant differences ($p < 0.05$, asterisk) between studied transects (1, 2, and 3; *t*-test) in Piaseczno reservoir.

Transect	LOI	Mg	Al	Si	S	Cl	K	Ca	Fe	Ga	Rb	Y	Mo	Ba	Pb
1	6.7	0.9	3.3	40.0	12.1	0.9	1.1	7.2	3.1	10.7	46.6	49.7	71.4	892.6	21.2
2	4.7	1.0	4.1	47.9	5.8	0.6	1.3	5.4	2.1	15.4	73.7	69.4	71.8	352.2	19.6
3	3.6	1.2	4.5	51.2	4.9	0.5	1.4	4.2	1.9	17.7	72.6	76.8	87.2	418.5	29.6
1 and 2			*		*	*	*		*	*	*	*		*	
1 and 3	*	*	*	*	*	*	*	*	*	*	*	*	*		*
2 and 3		*													*

Table 7. Correlation coefficient matrix for the contents of some elements (N = 36) of the sediment in Piaseczno reservoir (significant correlations are shown in bold). The remaining elements did not show significant correlations.

	LOI	Mg	Al	Si	P-tot	S-tot	Cl	K	Ca	Cr	Mn	Fe	Ga	Rb	Sr	Y	Mo	I
LOI	1	−0.61	−0.63	−0.87	**0.64**	**0.61**	**0.85**	−0.48	**0.76**	0.55	0.58	**0.60**	−0.24	−0.63	0.54	−0.74	−0.78	**0.63**
Mg		1	**0.96**	**0.72**	−0.65	−0.62	−0.75	**0.87**	−0.69	−0.43	−0.65	−0.53	0.61	**0.87**	−0.61	**0.78**	**0.79**	−0.62
Al			1	**0.74**	−0.61	−0.57	−0.79	**0.94**	**−0.77**	−0.40	−0.66	−0.52	**0.71**	**0.93**	−0.65	**0.84**	**0.80**	−0.64
Si				1	−0.78	−0.74	−0.97	**0.61**	**−0.87**	−0.54	−0.61	−0.73	0.41	**0.79**	−0.54	**0.90**	**0.89**	−0.57
P-tot					1	**0.99**	**0.79**	−0.60	0.49	**0.67**	0.16	**0.92**	−0.26	−0.63	0.52	−0.75	−0.74	0.23
S-tot						1	**0.75**	−0.58	0.43	**0.67**	0.11	**0.90**	−0.21	−0.58	0.54	−0.72	−0.72	0.20
Cl							1	−0.67	**0.90**	0.52	0.56	**0.70**	−0.49	−0.82	0.54	−0.90	−0.85	0.50
K								1	−0.61	−0.39	−0.49	−0.52	**0.71**	**0.89**	−0.69	**0.81**	**0.71**	−0.55
Ca									1	0.22	**0.71**	0.39	−0.61	−0.79	0.47	−0.82	−0.76	0.56
Cr										1	0.20	**0.81**	0.05	−0.45	0.33	−0.53	−0.56	0.37
Mn											1	0.15	−0.46	−0.60	0.49	−0.56	−0.68	**0.88**
Fe												1	−0.18	−0.62	0.34	−0.72	−0.70	0.25
Ga													1	**0.68**	−0.46	**0.62**	0.51	−0.43
Rb														1	−0.47	**0.89**	**0.76**	−0.57
Sr															1	−0.65	−0.75	**0.68**
Y																1	**0.90**	−0.61
Mo																	1	−0.73
I																		1

and sandstone values given by Turiekian and Wedepohl (1961). The elevated Cl concentration may be connected with salt plugs, which often occur in the region of sulphur ores (Polański 1974). The concentrations of trace elements in the clay rocks of Piaseczno lake catchment basin were either lower than or similar to (except for Mo, I) those of the shale rocks (Table 2) (Turiekian and Wedepohl 1961). The concentrations of most trace elements were higher in the sandstone (except for Pb, Ti) and carbonate rocks (except for Ni, Sr, Rb, Ti) when compared to those given by Turiekian and Wedepohl (1961). An especially high concentration of Mo was found in the sand rock (450 ×) and in the calcareous rock (ca. 445 ×). Pawłowski et al. (1965) found up to 3, 5% Sr in the rocks (sulphur ore) of this area. Such composition of the rocks reflects the regional pattern i.e. their natural background contents.

The value of enrichment factors indicated that sediment of Piaseczno reservoir is slightly polluted by antrophogenic trace elements. EF was not calculated for Mn and Fe because concentrations of those elements can largely vary between soils depending on the type of geological substrate. Elevated concentrations of Mn and Fe in the sediment may have natural source connected with their high level in Quarternary aquifer (Frankiewicz and Pucek, in press) which supplied the reservoir. On the other hand, some part of Fe and Mn may have an anthropogenic origin, because there is a chemical factory and a power station located ca. 8 and 30 km from the reservoir.

It is well known that the grain fraction and the content of organic matter determined the trace element distribution in the sediment. In the sediments of Piaseczno reservoir the clay silty fraction predominance allows to state that they have a high sorption capacity (Föstner and Wittmann 1983; Helios-Rybicka, 1986). Occurrence of a higher share of sandy fraction on 1 m depth may have connection with the appearance of Baranów sands on that depth. Sediments of Piaseczno lake are characterised by low amount of organic matter (LOI) similar to that found in oligotrophic lakes with low primary production and low input of allochthonous organic matter from their catchments (Korhola et al. 2002). The concentration of organic matter in Piaseczno lake was more comparable to that found in the large deep, high mountain Morskie Oko lake (Pasternak 1965), and to some small high mountain ponds (Dumnicka and Galas 2002). The contents of organic matter found in our study were much lower than those found in eutrophic lakes such as e.g. in Taihu Lake, China (Org-C 2.05–3.83%; N-tot 0.28–0.54%; P-tot 0.10–0.33%) (Wenchuan et al. 2001), or in Petersdorf Lake (Germany) (LOI 27–36%, N-tot 1.3–2.1%, P-tot 0.16%) (Kleeberg et al. 1999). Surprisingly the relationships between the amount of organic matter and concentration of trace elements (except I) were not found. Contrary to the results obtained in this study, an association between LOI and certain trace elements has been found in many works (Drbal 1991; Szarek-Gwiazda 1998; Rognerud and Fjeld 2001; El Bilali et al. 2002).

Obtained results showed differentiation of concentrations of most elements with respect to the lake depth. Samples from 1 m contained lower concentrations of Mg, S, K, Cr, Fe, Zn, Sr, and Mo than samples collected from deeper regions which may be connected with lower abundance of silt and clay fractions there, and hence lower sorption capacity at this depth. The tendency for certain elements (Zn, Pb, Mn and Ba) to be more abundant in deeper zones of the lake sediment was also found by Solecki and Chibowski (2000) and Abraham (1998). According to the latter author such situation was connected with the amount of clays and carbonate in the sediment.

On different transects different groups of elements dominated. Such differences may be caused by the following factors: 1. since Piaseczno lake is a young lake and the sediment layer is rather thin, the chemical composition of sediment may be influenced by deeper laying deposits; 2. wind exposition–transect 1 was the most exposed to waves and had the thinnest sediment bottom, whereas transect 2 and 3 were situated in the protected part of the lake. The occurrence of two groups of elements was also reflected by factor analysis. Group 1 represented elements whose sources are mainly living organisms while the second one reflected the dominant geochemical influence of the catchment area (coming mostly from rock weathering).

Correlation's matrix reflects detail relationships between the elements. The relationship, which was found between Fe and P, may result from their similar behaviour in the redox condition, which influences the processes of their accumulation and remobilisation from the sediment. The positive correlation between trace elements and Al is related to the abundance of clays (Horowitz et al. 1988; Abraham 1998). Thus, most of the variability of those element concentrations in the sediment can be explained by the Al concentration, which reflects its texture and mineralogy. Expected relationships between Fe and Mn and the trace elements were not found, whereas the hydrous Fe/Mn oxides are well known as 'scavengers' of micropollutants (Salomons and Förstner 1984).

Conclusion

The chemical composition of the sediment in Piaseczno reservoir created in the opencast sulphur mine reflects its natural, regional background. The sediment has a primarily mineral character with small amounts of organic matter. Concentrations of some major and trace elements differed in respect to studied transects and depths. The lowest concentrations of studied element being found at the depth of 1 m. Generally, the results show substantial chemical heterogeneity of the bottom sediment, which is probably connected with its allochthonous origin and also with the young age of the lake.

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