IOŚ-PIB OCHRONA ŚRODOWISKA I ZASOBÓW NATURALNYCH
ENVIRONMENTAL PROTECTION AND NATURAL RESOURCES 2015
DE GRUYTER OPEN
VOL. 26 NO 4(66): 40-47
DOI 10.1515/OSZN-2015-0022

Izabela Bojakowska*, Olimpia Kozłowska* , Bartosz Stec*

Trace elements in lake sediments of the Brda river catchment area

Pierwiastki śladowe w osadach jezior zlewni Brdy

*Prof. dr hab. Izabela Bojakowska, dr Olimpia Kozłowska, mgr Bartosz Stec – Polish Geological Institute – National Research Institute, Rakowiecka 4 St., 00-975 Warsaw, Poland, e-mail: izabela.bojakowska@pgi.gov.pl, olimpia.kozlowski@pgi.gov.pl , bartosz.stec@pgi.gov.pl.

Keywords: lake sediments, trace elements, pollution
Słowa kluczowe: osady jeziorne, pierwiastki śladowe, zanieczyszczenie

Abstract
Total of 54 samples (of sediments taken from the surface of 5-cm layer of profundal zone of lakes in the catchment of the river Brda) were tested in presented research. The collected samples were analysed for the concentrations of Ag, As, Ba, Cd, Co, Cr, Cu, Ni, Pb, Sn, Sr, V and Zn, and Al, Ca, Fe, Mg, Mn, P and S, using inductively coupled plasma atomic emission spectroscopy (ICP-AES), after sample digestion in *aqua regia*. The Hg concentration was determined from solid samples using atomic absorption spectroscopy (TMA). The organic carbon content was determined using the coulometric method. Sediments of most of lakes examined in the Brda catchment area are characterised by low concentrations of trace elements. Sediments contained an average of 0.9 mg/kg of Cd, 0.107 mg/kg of Hg, 8 mg/kg of Ni, 46 mg/kg of Pb, 8 mg/kg of As, 78 mg/kg of Ba, 12 mg/kg of Cr, 94 mg/kg of Zn, 3 mg/kg of Co, 12 mg/kg of Cu, 1.3 mg/kg of Mo, 105 mg/kg of Sr and 16 mg/kg of V. The presence of elevated concentrations of chromium, copper, nickel and vanadium is controlled by a geogenic factor – weathering of glacial deposits containing fragments of igneous and metamorphic rocks which are the source of heavy metals. The presence of elevated contents of Pb, Zn, Hg and Cd is caused by anthropogenic factor. Most of the lake sediments show low concentrations of As, Cd, Cr, Cu, Hg and Ni, which do not pose a threat to aquatic organisms. The concentrations of lead in almost half of the samples are elevated to a level at which a negative effect of this element can be observed. In the case of zinc, the proportion of such samples is about 25%.

Streszczenie
W zlewni rzeki Brdy zbadano osady 54 jezior, które zostały pobrane ze strefy profundalnej z powierzchniowej 5cm warstwy. W pobranych próbkach oznaczono zawartość Ag, As, Ba, Cd, Co, Cr, Cu, Ni, Pb, Sn, Sr, V i Zn oraz Al, Ca, Fe, Mg, Mn, P i S metodą ICP-OES, po roztworzeniu próbek w wodzie królewskiej oraz oznaczono zawartość Hg metodą TMA i węgla organicznego - metodą kulometryczną z próbki stałej. Większość zbadanych próbek charakteryzowała się niską zawartością pierwiastków śladowych. Osady zawierały średnio 0,9 mg/kg Cd,0,107 mg/kg Hg, 8 mg/kg Ni, 46 mg/kg Pb, 8 mg/kg As, 78 mg/kg Ba, 12 mg/kg Cr, 94 mg/kg Zn, 3 mg/kg Co, 12 mg/kg Cu, 1,3 mg/kg Mo, 105 mg/kg Sr i 16 mg/kg V. Stwierdzono, że obecność podwyższonych zawartości Cr, Cu, Ni i V w osadach jezior uwarunkowana jest czynnikiem geogenicznym - wietrzeniem utworów pochodzenia polodowcowego, zaś obecność podwyższonych zawartości Pb, Zn, Hg i Cd spowodowana jest czynnikiem antropogenicznym. W przeważającej ilości zbadanych osadów stężenia As, Cd, Cr, Cu, Hg, Ni były niskie i niestwarzające zagrożenia dla organizmów wodnych. W blisko połowie próbek zawartość ołowiu była podwyższona do poziomu, przy którym może być obserwowany negatywny wpływ tego pierwiastka na organizmy wodne, a w przypadku cynku w około 25% próbek.

1. INTRODUCTION

Under natural conditions, lake sediments are formed through the accumulation of allochthonous material derived from erosion and weathering of rocks occurring in the catchment area of a water body (including the accumulation of quartz and feldspar grains, carbonate minerals and clay minerals) and through the deposition of biogenic autochthonous material (which forms at the site of sedimentation) and inorganic autochthonous material. Inorganic autochthonous material is represented by chemical compounds, such as silica, calcium carbonate, iron and manganese hydroxides, iron sulphides, and calcium phosphate, which precipitate out of the water. Chemical composition of these sediments, including the concentration of trace elements, is controlled by the properties of rocks occurring in the catchment area of the lake and by climatic conditions [Bojakowska, Gliwicz 2009; Fei Zhang et al 2013].

In the recently accumulated sediments, elevated concentrations of a number of elements, including chromium, zinc, cadmium, copper, lead and mercury, are often observed compared to the concentrations of these components in the sediments that were formed during pre-industrial times [Aleksander-Kwaterczak, Prosowicz 2007; Cooke et al. 2007; Pulford et al. 2009; Tylmann 2004; Pompeani et al. 2013]. This is due to the human economic activity carried out in lake's catchment area, deposition of pollutants from the atmosphere and rainwater and melt water runoff [Rocher et al. 2004; Wildi et al. 2004; Cui et al. 2010; Taylor, Owens 2009]. Lake sediments are characterised by their ability to accumulate inorganic contaminants and countless types of organic pollutants, for example, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs) and organochlorine pesticides. The presence of high concentrations of potentially harmful metals in the sediments, such as Zn, Cu, Cr, Cd, Pb, Ni and Hg, as well as of persistent organic pollutants, adversely affects the quality of surface water environment. Contaminated sediments are a threat to organisms inhabiting them and participating in the biogeochemical transformations that play a crucial role in maintaining good water quality and distribution of organic matter. Contamination of modern water sediments is currently one of the most important environmental problems because of the potentially harmful impact on biological resources and often indirectly on human health. Contaminants found in sediments can accumulate in the trophic chain to a level that is toxic to aquatic organisms, especially predators [Radomski et al. 2006: Fu et al 2013]. They can also pose a risk to humans and animals consuming fish or shellfish inhabiting areas where such sediments occur [Vink 2009; Sorour, Harbey 2012; Xiao et al., 2013].

2. STUDY AREA

The Brda river is a 238-km long left tributary of the Vistula river. Its catchment area is 4627 km^2. The river flows from Lake Smołowe in the Bytów Lakeland northeast of the town of Miastko and enters the Vistula river at its 771 km in Bydgoszcz. According to the physiographic division, the Brda river catchment area belongs to the South-Baltic Lakeland [Kondracki 2002], occupying almost the whole Charzykowy Plain, the entire Brda Valley, south-western part of the Tuchola Forest, eastern part of the Krajeńskie Lakeland, the eastern Świecko Upland and a small part of the Toruń Valley. The Brda river catchment area is characterised by a late-glacial relief with hills and numerous lakes. Quaternary sediments that occur at the surface, mainly glacial tills and glaciofluvial sands, are typified by low contents of potentially harmful trace elements.

The Brda river basin is an agricultural and forest area. Agricultural land accounts for 48.6% of the catchment area, forests and semi-natural ecosystems – 45.8%, anthropogenic areas – 2.4%, and wetland – 0.2% (Hobot et al. 2012). Local exploitation of common raw mineral materials (clay, till, sand, peat) is a small hazard to the environment of this area. Major cities and towns in the Brda river catchment area are Bydgoszcz (population 356,200), Chojnice (population 39,900), Tuchola (population 13,900), Koronowo (population 11,000), Czersk (population 9,800) and Sępolno Krajeńskie (population 9,100).

In the Brda river basin, the Tuchola Forest National Park has been established to protect its outwash plain oligotrophic landscape. There are also landscape parks – Zaborski Landscape Park, Tuchola Landscape Park and Wdzydze Landscape Park – protected landscape areas, nature reserves and special areas of habitat conservation. The surface water environment in this area is polluted mainly because of agriculture and animal husbandry and by pollutant emissions from fuel burning for household and municipal needs and in transportation.

3. RESEARCH SCOPE AND METHODS

The study has used the research results of the National Environmental Monitoring running in order to monitor the concentrations of potentially harmful elements and persistent organic pollutants in recent sediments of rivers and lakes and to record their changes over time. During the implementation of the tasks of the State Environmental Monitoring, sediments of 54 lakes were surveyed in the Brda river catchment area in the period 1995–2014. Sediment samples were taken from a 5-cm-thick sediment layer of the profundal zone of the lakes, using a Van Veen sampler.

The samples collected were analysed for the concentrations of Ag, As, Ba, Cd, Co, Cr, Cu, Ni, Pb, Sn, Sr, V and Zn, and Al, Ca, Fe, Mg, Mn, P and S, using inductively coupled plasma optical emission spectrometry (ICP-OES), after sample digestion in *aqua regia*. The concentration of Hg was determined from solid samples using thermal decomposition amalgamation atomic absorption spectrometry (TDA AAS). The organic carbon content was determined using the coulometric method. In order to assess the research quality, reference lake sediment material WQB-3 was also analysed (standard – Trace Metals in Sediments, developed by the Aquatic Ecosystem Protection Branch, National Water Research Institute, Canada, Burlington, ON).

4. RESULTS AND DISCUSSION

The studies have shown that the average concentrations of trace elements in lake sediments of the Brda river catchment area are higher than the average concentrations of these elements in water sediments of Poland [Lis, Pasieczna 1995]. As regards the most harmful elements to aqueous organisms (Cd, Hg, Ni and Pb), the sediments contain the following amounts on an average: 0.9 mg/kg of Cd, 0.107 mg/kg of Hg, 8 mg/kg of Ni and 46 mg/kg of Pb. Considering the group of trace elements that are important for the environment quality, but pose a lesser threat to the biota, the sediments contain the following amounts on an average: 8 mg/kg of As, 78 mg/kg of Ba, 12 mg/kg of Cr, 94 mg/kg of Zn, 3 mg/kg of Co, 12 mg/kg of Cu, 1.3 mg/kg of Mo, 105 mg/kg of Sr and 16 mg/kg of V. Moreover, the sediments contain in an average of 0.086% of P, 0.46% of Al, 0.21% of Mg, 0.087% of K, 1.094% of S, 0.017% of Na, 11.58% of Ca, 1.62% of Fe and 9.18% of organic carbon (Table 1). Histograms of the concentrations of cadmium, mercury, lead and zinc in lake sediments of the Brda river catchment area are shown in Figure 1.

An elevated cadmium concentration, above 2 mg/kg, was found in the sediments of lakes Ślepe, Okonińskie and Orle, and an increased nickel concentration was recorded in, for example, Lake Jeleń and Lake Stobno. A mercury concentration of above 0.2 mg/kg was measured in the sediments from lakes Gwiazda, Milachowo and Ślepe, and a lead concentration exceeding 100 mg/kg

Table 1. The concentrations of some elements in lake sediments of the Brda river catchment area

Element	Detection limit	Mean	Geometric mean	Median	Minimum	Maximum	Standard deviation
	mg/kg						
Arsenic	3	8	6	6	<3	22	5
Barium	1	78	68	79	14	188	37
Chromium	1	12	9	9	1	47	10
Tin	2	<2	<2	<2	<2	3.4	0.8
Zinc	1	94	81	78	10	230	51
Cadmium	0.5	0.9	0.7	0.7	<0.5	2.8	0.6
Cobalt	1	3	2	2	1	8	2
Manganese	1	1277	773	753	50	10550	1634
Cooper	1	12	10	12	2	28	6
Molybdenum	0.5	1.3	1.0	1.0	<0.5	5.2	1.0
Nickel	1	8	7	7	1	24	5
Lead	3	46	37	34	6	141	31
Mercury	0.005	0.107	0.091	0.100	0.014	0.273	0.058
Silver	0.5	<0.5	<0.5	<0.5	<0.5	1.3	0.2
Strontium	1	105	78	96	6	298	69
Titanium	1	103	91	92	16	239	49
Vanadium	1	16	13	13	2	41	9
	%						
Phosphorus	0.005	0.121	0.105	0.111	0.011	0.401	0.070
Aluminium	0.01	0.55	0.41	0.36	0.05	2.12	0.48
Magnesium	0.01	0.210	0.191	0.180	0.027	0.590	0.094
Potassium	0.005	0.096	0.073	0.080	<0.01	0.330	0.076
Sulphur	0.005	0.979	0.862	0.970	0.149	2.182	0.455
Sodium	0.005	0.018	0.017	0.017	0.009	0.043	0.006
Calcium	0.01	12.38	7.49	13.65	0.18	31.34	8.58
Carbon org.	0.05	11.54	10.09	9.48	1.71	33.20	6.41
Iron	0.01	1.48	1.23	1.40	0.09	4.10	0.79

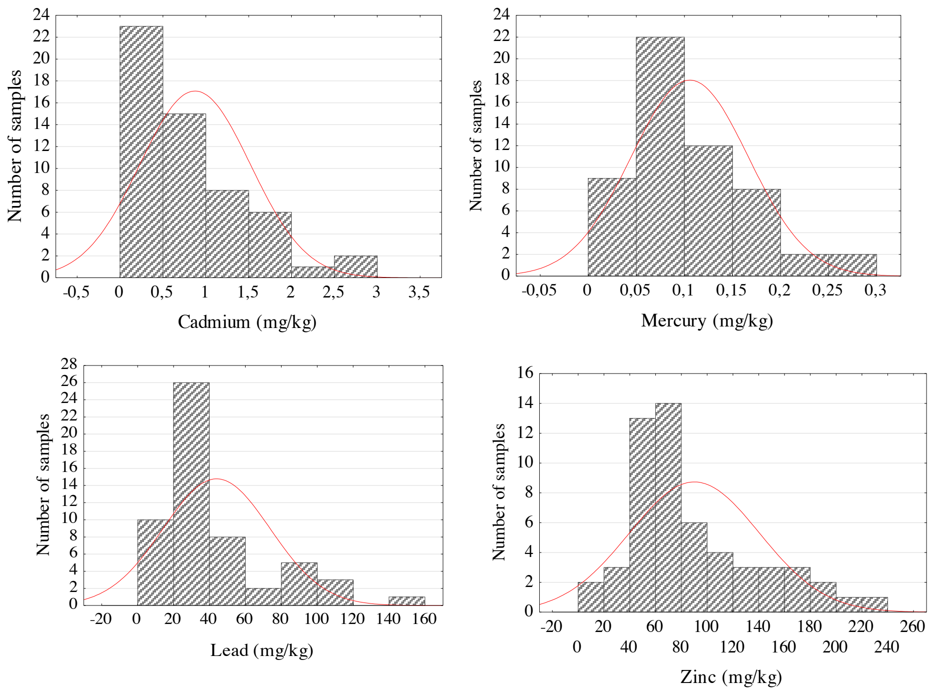

Fig. 1. Histograms of Cd, Hg, Pb and Zn contents in lake sediments

Table 2. Comparison of the concentrations of trace elements in the catchment areas of the Drawa, Biebrza and Brda rivers

Element	catchment areas of the Drawa river (n = 37)	catchment areas of the Biebrza river (n = 42)	catchment areas of the Brda river (n = 54)
Arsenic	8	7	8
Barium	75	105	78
Chromium	11	11	12
Zinc	97	88	94
Cadmium	0,9	0,8	0,9
Cobalt	3	3	3
Manganese	882	983	1277
Copper	13	16	12
Nickel	8	8	8
Lead	44	30	46
Mercury	0.108	0.112	0.107
Silver	0.5	<0.5	<0.5
Strontium	100	99	105
Vanadium	15	16	16

was found in, for example, Lake Długie (municipality Lipnica) and Lake Orle. It is worth noting that the presence of high zinc concentrations, more than 150 mg/kg, in the sediments of the following lakes: Długie, Okonińskie, Ślepe, Orle, Kamień, Gwiazda, Charzykowskie and Orłowskie. A chromium concentration of above 30 mg/kg was recorded, among others, in the sediments of lakes Charzykowskie, Sępoleńskie and Okonińskie, and an elevated copper concentration, above 20 mg/kg, was found in the sediments of lakes, for example, Jeleń, Orle and Gwiazda. An arsenic concentration of above 10 mg/kg was recorded in 12 lakes, including Lake Długie (municipality Lipnica), Lake Okonińskie and Lake Trzemeszno. Sediments of some lakes also reveal an increased concentration of molybdenum, for example, in lakes Borzyszkowskie, Lipczyno, Gwiazda and Drzycimskie. The presence of tin at a concentration above the determination limit was reported in the sediments sampled from lakes, among others, Orłowskie and Charzykowskie, and a silver concentration above the determination limit was detected only in the sediments of Lake Sępoleńskie and Lake Charzykowskie. A barium concentration exceeding 100 mg/kg was found in the sediments of 17 lakes, for example, Krzywe, Stobno and Sępoleńskie, and an elevated strontium concentration, above 200 mg/kg, was recorded in the sediments of the following lakes: Krasne, Gwiazda, Laska, Strzyżyny, Parzyn and Śpierewnik. A vanadium concentration of above 35 mg/kg was found in the sediments of lakes Stobno, Okonińskie and Jeleń. Sediments of the examined lakes are characterised by a low cobalt concentration, not exceeding 8 mg/kg.

The study has revealed spatial variation in the occurrence of trace elements in the sediments of the Brda river basin. Increased Cr, Cu, Ni and V concentrations were recorded in sediments of lakes that developed on moraine deposits. Lower concentrations were found in sediments of lakes in areas of glaciofluvial deposits. The slightly higher concentrations of Ba, Cr, Ni, V and Sr in the lake sediments than those in river sediments of Poland are of geogenic origin and result from sedimentation of materials originating from surface runoff in areas adjacent to the lakes. Glacial deposits, being subject to weathering and erosional processes, contain erratic boulders of igneous and metamorphic rocks, which are the source of these elements. Compared to the lake sediments in the Biebrza river catchment area, the sediments in the Brda river basin are characterised by lower concentrations of Ba and Cu but higher concentrations of Zn, Mn and Pb. However, compared to the sediments of the Drava river catchment area, the concentrations of trace elements are very similar [Bojakowska, Gliwicz 2009; Bojakowska et al. 2014] (Table 2).

Factor analysis has grouped the elements into four factors. The first factor, whose proportion is 29.1%, connects Co, Cu, Ni, V and Ti with Mg, Al and K. It can be called a geogenic–lithological factor associated with deposition of material derived from weathering of glacial deposits. The second factor, whose proportion is 16.3%, correlates As, Mo and Pb with organic carbon. Because of the presence of lead in this factor, it can be called an anthropogenic factor, because the increased concentration of this element in the environment is associated with human economic activity. The third factor, whose proportion is 14.6%, includes P, Ba, Fe and Mn. It is associated with the sedimentary conditions prevailing in the lakes profundal zone. The fourth factor, whose proportion is 13.9%, groups heavy metals and can be determined as an anthropogenic factor (Table 3).

It is worth noting the occurrence of markedly elevated concentrations of trace elements in sediments of lakes situated within the boundaries of landscape parks. The sediments of Lake Długie (Zaborowski Landscape Park), situated on a water route to Lake Laska, contain 22 mg/kg of As, 2.0 mg/kg of Cd, 0.254 mg/kg of Hg, 141 mg/kg of Pb and 230 mg/kg of Zn. The sediments of Lake Ślepe (Tuchola Landscape Park) contain 12 mg/kg of As, 2.8 mg/kg of Cd, 0.239 mg/kg of Hg, 102 mg/kg of Pb and 191 mg/kg of Zn. The sediments of two lobelia lakes, located in a nature reserve in the Brda river's headwaters, typically show greatly elevated concentrations of trace elements. The sediments of Lake Orle contain 2.4 mg/kg of Cd, 23 mg/kg of Cu, 110 mg/kg of Pb and 187 mg/kg of Zn, and the sediments of Lake Kamień – 1.8 mg/kg of Cd, 0.148 mg/kg of Hg, 95 mg/kg of Pb and 178 mg/kg of Zn.

There are also elevated concentrations of trace elements in sediments of lakes that are used for recreational purposes, especially those on which recreational and agrotourism centres are situated, for example, the sediments of Lake Okonińskie contain 19 mg/kg of As, 2.6 mg/kg of Cd, 0.190 mg/kg of Hg, 102 mg/kg of Pb and 206 mg/kg of Zn, and the sediments of Lake Kiedrowickie contain 87 mg/kg of Pb and 148 mg/kg of Zn. Elevated concentrations of trace elements were also found in the sediments of Lake Gwiazda (1.7 mg/kg of Cd, 0.273 mg/kg of Hg, 95 mg/kg of Pb and 174 mg/kg of Zn) with the village of Borowy Młyn on its shore and in the sediments of Lake Charzykowskie (1.3 mg/kg of Ag, 47 mg/kg of Cr, 3 mg/kg of Sn and 163 mg/kg of Zn) with the holiday villages of Charzykowy and Kopernica.

Elevated concentrations of trace elements, such as lead, zinc and mercury, and locally silver and tin, in sediments of some lakes are caused by the anthropogenic factor. In the Brda catchment area, these elements have been released into the environment primarily as a result of the following processes and activities: (1) burning of coal (Hg, Zn), (2) road transport (Pb, Zn Cd), (3) destruction of building and finishing materials by atmospheric agents (Zn, Pb), (4) use and maintenance of canoes, boats (Zn, Cu, Cd, Hg, Sn), (5) fishing and angling (lead weights of fishing nets and rods) and (5) hunting (lead and arsenic are constituents of shot pellets, mercury is a constituent of primers).

Sediments of most of the lakes analysed within the study show relatively low concentrations of trace elements. The concentrations of As, Cd, Cr, Cu, Hg, Ni, Pb and Zn are lower than their *TEC* (*threshold effect concentration)* levels, which are the lower limits for harmful effects on aquatic organisms (MacDonald et al. 2000). The concentration of arsenic is higher than its TEC value (10 m/kg) in 11 samples, of cadmium (1 mg/kg) in 29.09% of samples, of chromium (43 mg/kg) in 1 sample, of mercury (0.18 mg/kg) in 5 samples, of nickel (2 mg/kg) in 1 sample, of lead (36 mg/kg) in 45.45% of samples and of zinc (123 mg/kg) in 23.63% of samples (Figure 2). None of the samples has yielded a copper concentration value greater than the *TEC,* which is 32 mg/kg. Elemental concentrations exceeding the *PEC (probable effect concentration)* values, which are the lower limits for harmful effects on organisms, have been found only in the sediments of Lake Długie where the concentration of lead is much greater than its PEC value (128 mg/kg). The assessment of the contamination level of lake sediments in the Brda river basin is shown in a map (Figure 2).

The assessment of contamination level of lake sediments was also made with the use of geoaccumulation indices ($I_{geo} = \log_2 C/1.5 \times B$, where C is the elemental concentration and B is the geochemical background level) introduced by Müller (Förstner 1989). These were determined using the values of regional geochemical background. Based on the geoaccumulation indices, it has been found that approximately 47.3% of analysed samples represent uncontaminated sediments with the geoaccumulation indices 0 and 1, and 50.9% of samples represent moderately contaminated sediments with the geoaccumulation indices 2 and 3. There is only one lake of strongly contaminated sediments with the geoaccumulation index 4. The lake sediment contamination is commonly due to very high lead and mercury concentrations (Table 4).

Table 3. Results of factor analysis of elemental concentrations in lake sediments in the Brda river basin

	Factor 1	Factor 2	Factor 3	Factor 4
Arsenic	0.072	0.795	0.366	0.136
Barium	0.452	−0.124	0.814	0.062
Chromium	0.554	−0.177	0.196	0.688
Tin	−0.050	0.311	0.188	0.767
Zinc	0.436	0.281	0.347	0.679
Cadmium	0.131	0.427	0.354	0.507
Cobalt	0.978	0.044	0.105	0.123
Manganese	−0.010	−0.006	0.916	0.097
Copper	0.758	0.322	0.293	0.323
Molybdenum	−0.072	0.782	−0.116	−0.046
Nickel	0.953	0.046	0.129	0.138
Lead	0.303	0.791	0.092	0.366
Mercury	0.340	0.225	0.570	0.584
Silver	−0.110	−0.264	0.188	0.787
Strontium	−0.266	−0.546	0.157	−0.223
Titanium	0.804	0.242	0.192	0.027
Vanadium	0.911	0.169	0.186	0.177
Phosphorus	0.024	−0.008	0.789	0.308
Aluminium	0.947	0.090	−0.043	0.145
Magnesium	0.817	−0.214	0.149	−0.090
Potassium	0.975	−0.128	0.037	0.058
Sulphur	−0.049	0.578	0.362	−0.074
Sodium	0.068	0.093	0.033	0.408
Calcium	−0.507	−0.496	0.103	−0.349
Carbon org.	−0.143	0.867	−0.107	0.096
Iron	0.299	0.101	0.757	0.111
Expl. Var.*	7.862	4.389	3.950	3.742
Prp. Totl.**	0.291	0.163	0.146	0.139

* Explained variance.
** - Total proportion of variance.

Table 4. Assessment of the contamination level of lake sediments (geochemical index)

I_{geo}	Class of sediment	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	Zn	Total
		Number of samples									
0	Uncontaminated sediments	27	34	44	30	24	22	41	4	38	2
1	Uncontaminated to moderately polluted sediments	20	12	9	14	27	21	11	24	15	24
2	Moderately polluted sediments	8	9	2	6	4	12	3	18	2	16
3	Moderately to strongly polluted sediments				5				8		12
4	Strongly polluted sediments								1		1

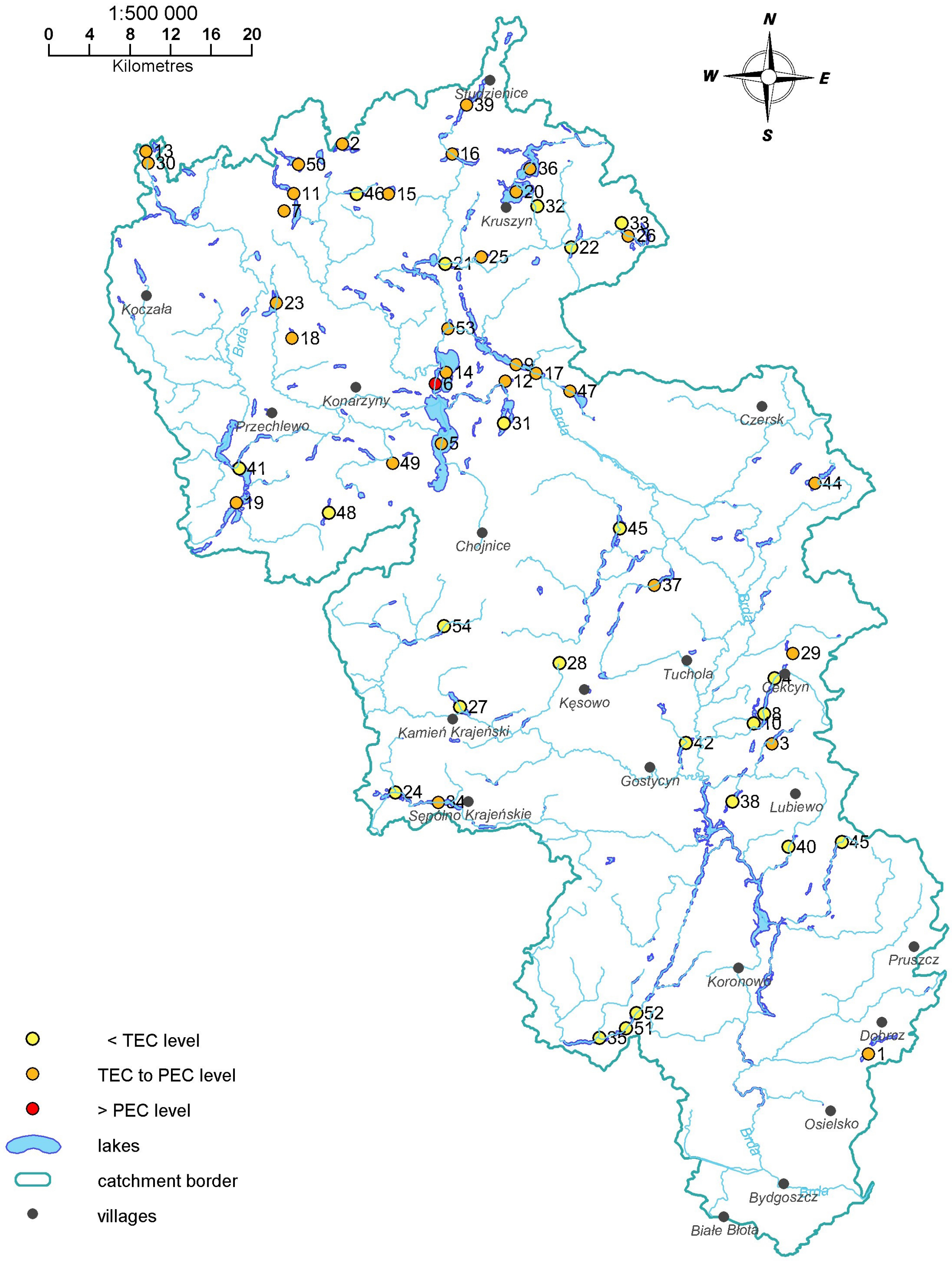

Fig. 2. Estimation of pollution lake sediments of the catchment areas of the Brda river according to the criteria TEC and PEC. 1, Borówno; 2, Borzyszkowskie; 3, Bysławskie; 4, Cekcyńskie; 5, Charzykowskie; 6, Długie (municipality Śliwice); 7, Długie (municipality Lipnice); 8, Drzycimskie; 9, Dybrzyk; 10, Gwiazda; 11, Gwiazdy; 12, Jeleń; 13, Kamień; 14, Karsińskie; 15, Kiedrowickie; 16, Kielsk (Kielskie); 17, Kosobudno; 18 , Krasne; 19, Krępsko; 20, Kruszyńskie; 21, Laska; 22, Leśno Dolne; 23, Lipczyno; 24, Lutowskie; 25, Milachowo; 26, Młosino; 27, Mochel; 28, Obrowo; 29, Okonińskie; 30, Orle; 31, Ostrowite; 32, Parzyn; 33, Raduń; 34, Sępoleńskie; 35, Słupowskie; 36, Somińskie; 37, Stobno; 38, Strzyżyny; 39, Studzienicki; 40, Suskie Wielkie; 41, Szczytno; 42, Szpitalne; 43, Ślepe; 44, Śpierewnik; 45, Świekatowskie; 46, Trzebielsk; 47, Trzemeszno; 48, Tuczno; 49, Węgorzyno; 50, Wiejskie; 51, Wierzchucińskie D.; 52, Wierzchucińskie M.; 53, Witoczno; 54, Zamarte.

5. CONCLUSIONS

1. Water sediments of most of the lakes examined in the Brda river catchment area are characterised by low concentrations of trace elements. The presence of elevated concentrations of chromium, copper, nickel and vanadium is controlled by a geogenic factor – weathering of glacial deposits containing fragments of igneous and metamorphic rocks, which are the source of heavy metals.
2. Clearly, elevated concentrations of trace elements have been found in sediments of some lakes located within landscape parks, for example, Lake Długie (Zaborowski Landscape Park), Lake Ślepe (Tuchola Landscape Park) and the lobelia lakes of Orle and Kamień.
3. The presence of elevated concentrations of trace elements has been recorded in sediments of some lakes with recreation centres and agrotourism sites on their shores, for example, in the following lakes: Okonińskie, Kiedrowickie, Gwiazda and Charzykowskie.
4. Most of the lake sediments show low concentrations of As, Cd, Cr, Cu, Hg and Ni, which do not pose a threat to aquatic organisms. The concentrations of lead in almost half of the samples are elevated to a level at which a negative effect of this element can be observed. In the case of zinc, the proportion of such samples is 23.63%. In the sediments of Lake Długie, the lead concentration is so high that it can frequently cause negative effects on living organisms.

REFERENCES

ALEKSANDER-KWATERCZAK U., PROSOWICZ D., 2007. Distribution of Cd and Pb in the lake sediments cores from the Hańczańska Bay (Wigry Lake, NE Poland). Limnological Review 7(4): 215-219.

BOJAKOWSKA I., GLIWICZ T., 2009. Geochemical characteristics of the Biebrza river catchment lake sediments. In: Problems of water protection in the Bug and Narew Rivers catchments. p. 57-66.

BOJAKOWSKA I., MAŁECKA K., STEC B. 2014. Pierwiastki śladowe w osadach jezior zlewni Drawy. Geochemia i Geologia Środowiska Terenów Uprzemysłowionych. (red. Marek Pozzi). Wyd. PA NOVA SA. Gliwice. p. 81-94.

COOKE C. ABBOTT M., WOLFE A. KITTLESON J. 2007. A Millennium of Metallurgy Recorded by Lake Sediments from Morococha, Peruvian Andes Environ. Sci. Technol. 41: 3469-3474

CUI Q., BRANDT N., SINHA R., MALMSTRÖM M. 2010. Copper content in lake sediments as a tracer of urban emissions: evaluation through a source-transport-storage model. Sci. Total Environ. 408 (13): 2714-25.

FEI ZHANG, ZHANGDONG JIN, FUCHUN LI, JIMIN YU, CHEN-FENG YOU, LING ZHOU 2013. The dominance of loess weathering on water and sediment chemistry within the Daihai Lake catchment, northeastern Chinese Loess Plateau. Applied Geochemistry 35: 51–63.

FÖRSTNER U., 1989. Contaminated sediments. Lectures on environmental aspects of particle-associated chemicals in aquatic systems. (Lecture Notes in Earth Sciences 21). Springer-Verlag.

FU J., HU X., TAO X., YU H, ZHANG X. 2013. Risk and toxicity assessments of heavy metals in sediments and fishes from the Yangtze River and Taihu Lake, China. Chemosphere 93(9): 1887-95.

HOBOT A., BANASZAK K., STOLARSKA M., SOWIŃSKA K., SERAFIN R., STACHURA A. 2012. Warunki korzystania z wód zlewni rzeki Brdy (SCWP: DW0601, DW0602, DW0603, DW0604, DW0605, DW0607, DW0609) – Etap 1 Dynamiczny bilans ilościowy zasobów wodnych. rzgw.gda.pl/cms/fck/uploaded/ZGPW_rozporzadzenia/Bilansowanie zasobów_Brda.pdf

KONDRACKI J. 2002. Geografia regionalna Polski. Wyd. Naukowe PWN.

LIS J., PASIECZNA A. 1995. Atlas geochemicznych Polski 1: 2500000. Państwowy Instytut Geologiczny. Warszawa.

MACDONALD D., INGERSOLL C., BERGER T. 2000. Development and Evaluation of consensus-based Sediment Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. Archives of Environmental Contamination and Toxicology 39: 20–31.

POMPEANI D.P., ABBOTT M.B., STEINMAN B.A., BAIN D.J. 2013. Lake Sediments Record Prehistoric Lead Pollution Related to Early Copper Production in North America. Environ. Sci. Technol. 2013, 47 (11): 5545–5552.

PULFORD I.D., MACKENZIE A.B., DONATELLO S., HASTINGS L. 2009 – Source term characterization using concentration trends and geochemical associations of Pb and Zn in river sediments in the vicinity of a disused mine site: Implications for contaminant metal dispersion processes. Environ Poll 157: 1649-1656.

RADOMSKI P., HEINRICH T., JONES T., RIVERS P., TALMAGE P. 2006. Estimates of Tackle Loss for Five Minnesota Walleye Fisheries. North American Journal of Fisheries Management 26: 206–212.

ROCHER V., AZIMI S., GASPERI J., BEUVIN L., MULLER M., MOILLERON R., CHEBBO G. 2004. Hydrocarbons and metals in atmospheric deposition and roof runoff in Central Paris. Water, Air, and Soil Pollution 159: 67-86.

SOROUR J., HARBEY D. 2012. Histological and ultrastructural changes in gills of tilapia fish from Wadi Hanifah Stream, Riyadh, Saudi Arabia. J. Am. Sci. 8(2):180-186.

TAYLOR K., OWENS P. 2009 - Sediments in urban river basins: a review of sediment–contaminant dynamics in an environmental system conditioned by human activities. J Soils Sediments (2009) 9: 281–303.

TYLMANN W. 2004. Heavy metals in recent lake sediments as an indicator of 20th century pollution: Case study on lake Jasień. Limnological Review 4 (2004): 261–268.

VINK J. 2009. The origin of speciation: Trace metal kinetics over natural water/sediment interfaces and the consequences for bioaccumulation. Environmental Pollution 157: 519-527.

WILDI W., DOMINIK J., LOIZEAU J., THOMAS R. FAVARGER P. HALLER L., PERROUD A., PEYTREMANN C. 2004 - River, reservoir and lake sediment contamination by heavy metals downstream from urban areas of Switzerland. Lakes & Reservoirs: Research & Management 9 (1): 75-87.

XIAO R., BAI J., HUANG L., ZHANG H., CUI B. LIU X. 2010. Distribution and pollution, toxicity and risk assessment of heavy metals in sediments from urban and rural rivers of the Pearl River delta in southern China. Ecotoxicology. 22(10): 1564-75.