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Lead in the bottom sediments of water bodies in the Upper Silesia region (southern Poland)

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ABSTRACT

The purpose of the study was to determine the extent to which the bottom sediments of water bodies in the Upper Silesia region in southern Poland are contaminated with lead; an attempt was also made to determine the factors that condition spatial differences in the concentration of this element between individual water bodies. Lead content was determined in sediment samples of 0.25 g each at Activation Laboratories Ltd. (Canada) using the ICP method with a lead detection limit of 5 ppm. Lead was found in the bottom sediments of water bodies examined in amounts ranging from 32 to 3340 ppm. In only seven out of the 50 water bodies examined did bottom sediments contain lead in amounts that is considered natural; in the remaining water bodies, natural levels were exceeded pointing to probable anthropogenic pollution. In order to confirm the correlation found between the amount of lead in the bottom sediments of water bodies in the Upper Silesia region and the intensity of human impact, additional studies will need to be conducted. Lead content in bottom sediments was in some cases several times higher than that in the sediments within the substrate of water body basins.

Keywords: Lead; Sediments; Water reservoirs; Pollution levels; Environmental pollution; Upper Silesia region

1. Introduction

Lead is considered a toxic element and its concentrations are relevant to human health and the environment [1–4]. The average lead concentration in the Earth's crust is estimated at about 12.5 ppm; owing to the poor solubility of most lead compounds, its water concentrations range from 0.002 to 0.03 ppm [5]. Natural lead concentrations in stream sediments in Europe are estimated to be around 14 ppm [6]. The geochemical background for lead in surface water sediments in Poland is estimated at 13 ppm [7], and for surface water sediments in the Upper Silesia region is 59 ppm [8].

Industry (mining and non-ferrous metal smelting) is a major source of environmental lead pollution. In many regions of the world, the transport industry is also considered a major polluter, but effective efforts to eliminate lead as a fuel component have brought the expected results, reducing pollution. Elevated lead concentrations are associated with the use of fertilisers in agriculture.

Lead concentrations in polluted water may range from 21 to 35 ppm [5]. Record high concentrations of lead include 655 ppm found in bottom sediments of the Elbe River near Hamburg; 1,200 ppm measured in bottom sediments of the Biała Przemsza River close to a non-ferrous metal smelter [5]; and 2,670 ppm in sediments of polluted rivers in England [9].

Lead concentrations in the natural environment are monitored particularly closely. Studies of bottom sediments accumulated in water bodies are of special importance here, since the concentration of lead in these sediments is a good indicator of water pollution and of the environmental conditions that prevail in the catchment in question. Such studies are particularly expedient in the case of sediments collected from water bodies that are used for various purposes, especially to supply water (for agricultural, industrial or municipal purposes), for recreational purposes, to breed fish and other aquatic organisms.

The purpose of the study was to determine the extent to which the bottom sediments of water bodies in the Upper Silesia region in southern Poland are contaminated with lead; an attempt was also made to determine the factors that condition spatial differences in the concentration of this element between individual water bodies in the region. Another purpose was to assess lead concentrations in bottom sediments in comparison to substrate sediments in water body basins and to demonstrate the scale of anthropogenic lead enrichment of bottom sediments, and thus also to assess the cumulative impact of water bodies.

2. Materials and methods

A total of 50 water bodies located in the Upper Silesia region were selected for study purposes (Fig. 1). These included flooded mineral workings (water bodies 1–31), reservoirs impounded by dams (water bodies 32–34), water bodies in subsidence basins and hollows (water bodies 35–42) and levee ponds (water bodies 43–50). Some of those are polygenetic.

The lithological features of the substrates of the water bodies investigated are different (Fig. 2). In most cases, these substrates are sandy Quaternary formations; Triassic or Carboniferous formations are found less frequently in basin substrates [10]. As concerns the geology of the area studied, Carboniferous formations that contain coal are present; in the north and east, these are overlaid by Triassic rocks with deposits of zinc and lead ores. Above these strata, Tertiary deposits can be found in some locations in the south and west; at the boundaries of the area and in fossil valleys, Quaternary formations are generally present on the surface. The geochemical background of geological formations occurring on the surface varies accordingly. For lead, it is around 50 ppm; only in the area where ore-bearing Triassic rocks are present, it is estimated to be much higher, since average values as high as 130 ppm Pb are found there nowadays (with a median of 44 ppm Pb) [7,8].

The water bodies studied are mainly located within the Katowice conurbation which is formed by 33 cities and towns in the area from Jaworzno in the east to the vicinity of Gliwice in the west. Three more water bodies are situated in the Rybnik area, and one in the Oświęcim area. This is one of the most urbanised areas both in Poland and in Europe [11]. It has a very high population density, which exceeds 4,000 people per square kilometre in the central part of the Katowice conurbation. Important mineral resources, such as coal, zinc and lead ores, iron ores (no longer mined), sands, gravels, dolomites, etc. can be found in the area. Zinc and lead as well as iron ores were already mined in the early Middle Ages, while coal mining started in the late eighteenth century. Along with the extraction of these resources, iron and non-ferrous metal smelting as well as other branches of manufacturing industry developed. The area is among the most industrialised regions in Poland and the intensive industrialisation process has continued there uninterrupted since the end of the eighteenth century [11]. Agriculture developed on the outskirts of urban and industrial areas but it has been of much lesser importance in comparison to the enormous industrial potential of the region (especially with respect to the mining, fuel and energy and metallurgical industries).

Thus, this is an area where economic activity has developed for several centuries, and the water bodies discussed have been subject to strong but diverse human impact [12]. These are mostly urban and industrial pressures, and in some cases also agricultural ones; conditions referred to as quasi-natural are the least frequent (Table 1).

Samples of bottom sediments from 50 water bodies of various origins were collected from the ice cover using a Van Veen sampler with a capacity of 2.5 dm^3. Of the 50 water bodies studied, 20 were selected for studies of sediments present in the vicinity of their basins. These were water bodies in flooded sand workings. Owing to the lithological and chronological homogeneity of the formations situated close to their basins, these sites were considered the most representative from the point of view of the determination of the magnitude of anthropogenic impact. In these cases, samples were collected directly using polystyrene sediment core samplers. The samples collected were packed in polyethylene bags for transport and storage.

After having been dried at 105°C, sediment samples were homogenised in a porcelain mortar and screened through polyethylene meshes. Lead concentration measurements were performed at Activation Laboratories Ltd. in Canada using the ICP method.

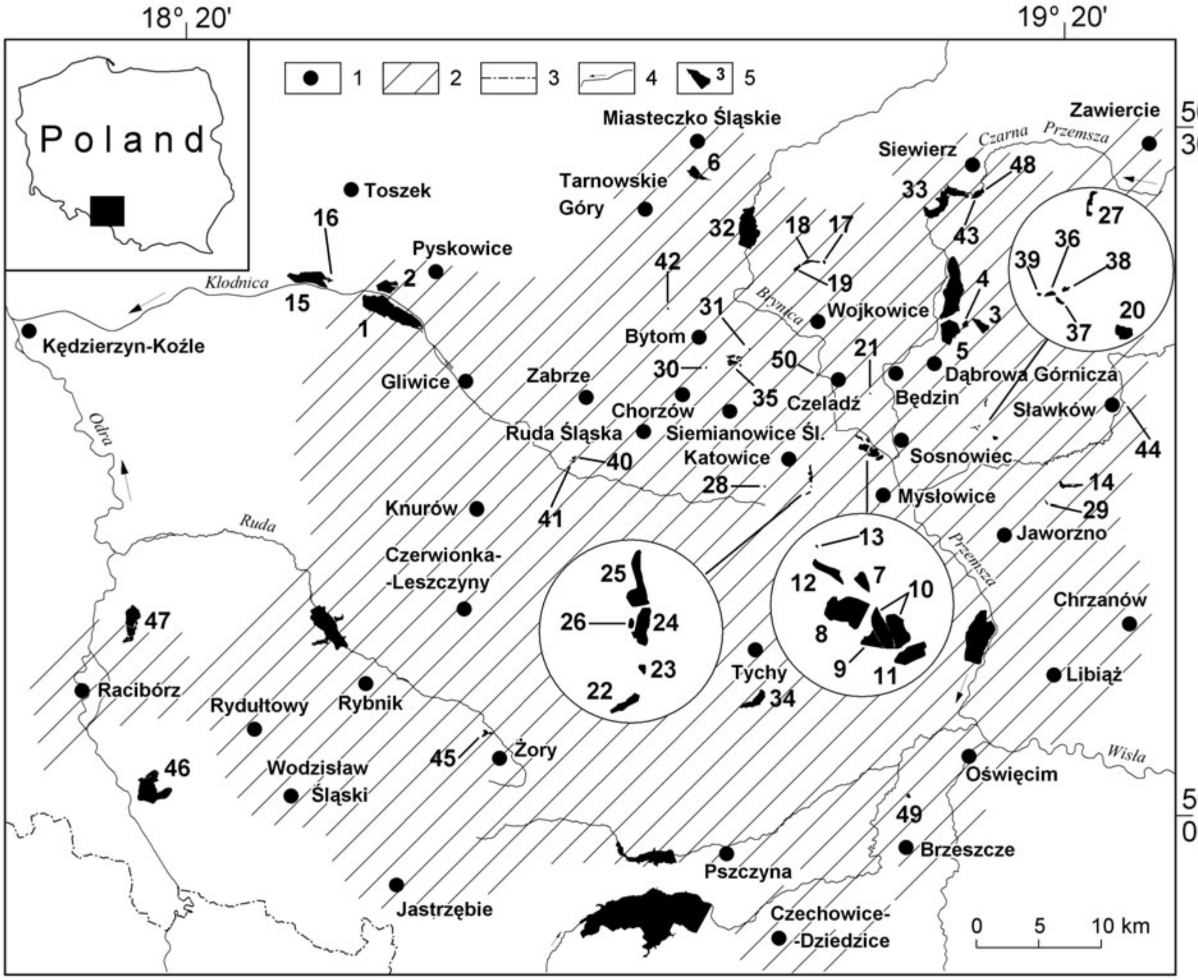

Fig. 1. Study area and the water bodies examined: 1—major cities, 2—urban and industrial areas, 3—state border, 4—surface waterways, 5—water bodies and the location of the water bodies examined (1—Dzierżno Duże, 2—Dzierżno Małe, 3—Pogoria I, 4—Pogoria II, 5—Pogoria III, 6—Chechło, 7—Stawiki, 8—Morawa, 9—Hubertus I, 10—Gliniok (eastern), 11—Hubertus II, 12—Borki, 13—Borki Małe, 14—Sosina, 15—Pławniowice, 16—Mały Zalew, 17—Rogoźnik (so-called upper i.e. eastern), 18—Rogoźnik I, 19—Rogoźnik II, 20—Balaton, 21—Czeladź Norwida, 22—Łąka, 23—Kajakowy, 24—Milicyjny, 25—water body without name, 26—Ozdobny, 27—Sosnowiec—Kązimierz (Park Leśna), 28—Gliniok (Western), 29—Jaworzno (Koparki), 30—Amendy, 31—water reservoir in Piekary Śląskie—Brzezinach, 32—Kozłowa Góra, 33—Przeczyce, 34—Paprocany, 35—Żabie doły, 36 –Bobrek flooding, 37—Sosnowiec Klimontów—southern bowl, 38—Sosnowiec Klimontów—eastern bowl, 39—Sosnowiec Klimontów—northern bowl, 40—Zabrze Makoszowy—on the road, 41—Zabrze Makoszowy—in forest, 42—Przy Leśnej, 43—ponds in backwater zones of Przeczyce water reservoirs, 44—Sławków, 45—Żory, 46—Lubomia, 47—Łężczok, 48—pond in Kuźnica Sulikowska in the Mitręga valley, 49—s ponds in the neighbourhood of Harmęże, 50—Przetok).

Sample aliquots of 0.25 g were digested with 10 ml of HCl–HNO_3–$HClO_4$–HF at 200°C to fuming and were then diluted to 10 ml with diluted aqua regia. This leach is partial for magnetite, chromite, barite and other spinels and potentially massive sulphides. In-lab standards (traceable to certified reference materials) or certified reference materials are used for quality control. Samples are analysed using a Varian Vista 735 ICP. The lower detection limit for lead in bottom sediments was 5 ppm, while the upper detection level was 5,000 ppm.

The concentration of lead in bottom sediments in relation to levels considered natural can be assessed using a simple ratio of the value measured to the geochemical background (Eq. (1)), which also indirectly indicates the pollution level. The proposed new formula (Eq. (1)) better reflects the specific character of lead presence in areas strongly affected by human

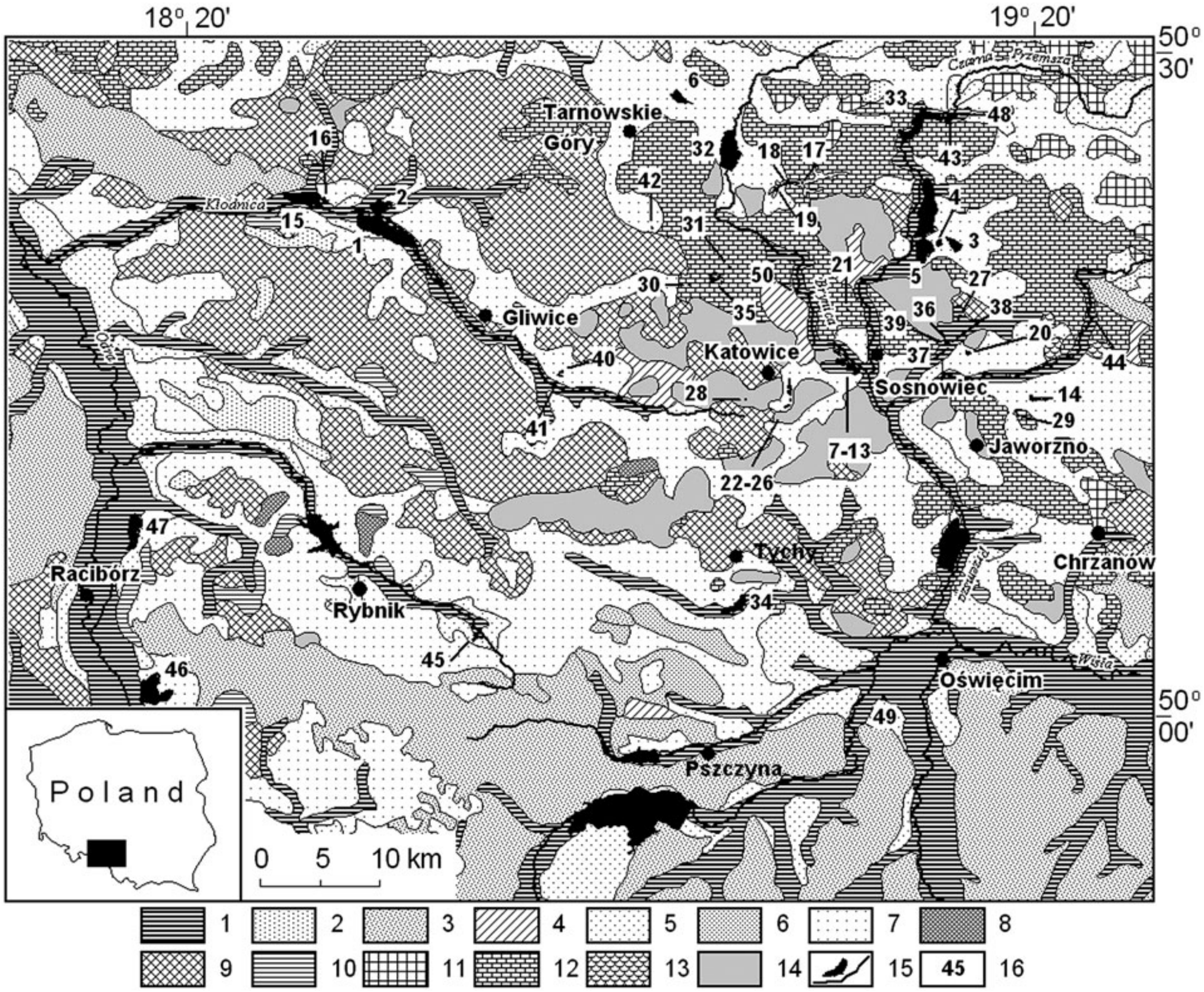

Fig. 2. Water bodies examined and surface formations—simplified [10]: 1—sands, gravels, alluvial soils, peat and silts (Holocene); 2—aeolian sands, locally in dunes (Quaternary); 3—loesses, sandy loesses and loess-like dusts (Quaternary); 4—clays, sands and clays with gruss, solifluctive-deluvial (Pleistocene); 5—sands, gravels and alluvial loams (Pleistocene); 6—marginal clays, loams and sands (Pleistocene); 7—outwash sands and gravels (Pleistocene); 8—end moraine gravels, sands, boulders and clays (Pleistocene); 9—glacial tills, glacial till waste and glacial sands and gravels (Pleistocene); 10—organodetritic limestones, sulphur-bearing limestones, gravels, clays, loams, sands, locally gypsum and lignite (Neogene); 11—limestones, marls, dolomites, mudstones, sandstones, claystones, with flints and siderite insertions (Jurassic); 12—claystones, mudstones, sandstones, limestones, dolomites, marls, oolithic limestones, gypsum, anhydrite, iron ores (Triassic); 13—conglomerates, arkosic sandstones, mudstones, claystones (Perm); 14—sandstones, conglomerates, claystones, mudstones, greywackes, coal (Carboniferous); 15—waterways and water bodies; 16—water body labels (see Fig. 1).

impact than the previously used geo-accumulation index developed by Müller [13]; it explicitly states the number of times the geochemical background is exceeded and is expressed as follows:

$$I_{\mathrm{RE}} = \frac{C_{\mathrm{BS}}}{C_{\mathrm{GB}}} \qquad (1)$$

where I_{RE}—the ratio of the value measured to the geochemical background (dimensionless number); C_{BS}—the average concentration of the element in question in bottom sediments; and C_{GB}—the geochemical background level for the element in question in bottom sediments.

The ratio of the value measured to the geochemical background calculated in this manner exceeds unity if the concentration of the element is higher than the geochemical background (the higher the concentration, the higher the ratio) and is below unity when this level is not reached.

Table 1
Land use in the catchments of the water bodies examined

Catchment (with its outlet specified)	Ref. nos. of water bodies examined (see Fig. 1)	Water	Urban and industrial areas	Forest	Agricultural land and wasteland	Water	Urban and industrial areas	Forest	Agricultural land and wasteland	Catchment area
		Share of catchment area in km^2				Share of catchment area in %				km^2
Kłodnica River down to the outlet from the Dzierżno Duże water body	1	10.5	172.0	127.2	232.8	1.9	31.7	23.4	42.9	542.5
Drama River down to the outlet from the Dzierżno Małe water body	2	1.4	12.7	13.3	103.2	1.1	9.7	10.2	79.0	130.6
Pogoria Stream down to the outlet from the Pogoria III water body	3–5	3.0	5.8	9.9	3.8	13.5	25.9	44.0	16.7	22.6
Catchment of water bodies where the Rawa River flows into the Brynica River	7–10,12–13	1.0	1.6	0.3	0.2	33.0	51.3	9.9	5.8	3.1
Catchment of the Hubertus II water body	11	0.1	0.2	0.0	0.0	21.2	63.6	3.0	12.1	0.3
Catchment of the Sosina water body	14	0.4	0.0	1.8	0.3	15.9	1.2	72.2	10.6	2.5
Toszecki Stream (outlet from the Pławniowice water body)	15–161	3.0	4.7	25.8	85.6	2.5	3.9	21.7	71.9	119.1
Jaworznik Stream down to the outlet from the Rogoźnik II water body	17–19	0.3	0.7	4.1	10.9	2.1	4.1	25.5	68.2	15.9
Catchment of the Balaton water body	20	0.1	0.3	0.6	0.0	9.8	29.3	60.9	0.0	0.9
Catchment of the Czeladź Norwida water body	21	0.0	0.0	0.0	0.0	20.0	0.0	0.0	80.0	0.1
Leśny Stream down to the outlet from the Łąka water body	22–26	0.4	5.3	5.4	0.8	3.3	44.7	45.7	6.3	11.9
Catchment of the Kazimierz water body (Park Leśna)	27	0.1	0.1	0.2	0.1	12.5	12.5	50.0	25.0	0.4
Catchment of the Gliniok water body (Western)	28	0.0	0.1	0.0	0.0	18.5	65.4	16.0	0.0	0.1
Catchment of the Jaworzno water body (Koparki)	29	0.1	0.2	0.1	0.0	16.1	67.7	16.1	0.0	0.3
Catchment of the Amendy water body	30	0.0	0.1	0.2	0.1	0.3	4.1	16.0	47.6	32.3

(*Continued*)

Table 1
(*Continued*)

Catchment (with its outlet specified)	Ref. nos. of water bodies examined (see Fig. 1)	Water	Urban and industrial areas	Forest	Agricultural land and wasteland	Water	Urban and industrial areas	Forest	Agricultural land and wasteland	Catchment area
		Share of catchment area in km^2				Share of catchment area in %				km^2
Catchment of the water body in Piekary Śląskie—Brzeziny	31	0.0	0.6	0.0	0.3	1.1	62.0	1.1	35.9	0.9
Brynica River down to the outlet from the Kozłowa Góra water body	6,32	5.0	11.0	90.1	100.0	2.4	5.3	43.7	48.5	206.1
Czarna Przemsza River (outlet from the Przeczyce water body)	33,43, 48	3.7	27.6	118.5	146.4	1.2	9.3	40.0	49.4	296.2
Gostynka down to the outlet from the Paprocany water body	34	2.6	15.6	63.1	51.5	2.0	11.7	47.5	38.8	132.7
Catchment of the Żabie Doły water bodies	35	0.4	1.2	0.0	1.7	12.0	36.7	0.0	51.2	3.2
Catchment of the Bobrek Stream down to the Klimontów profile	36–39	0.5	27.9	21.9	31.7	0.6	34.1	26.7	38.6	81.9
Catchment of the water bodies in Zabrze Makoszowy	40–41	0.1	0.1	2.7	0.2	2.6	4.5	87.1	5.8	3.1
Catchment of the Przy Leśnej water body	42	0.0	0.2	0.3	0.1	0.6	3.5	25.1	50.7	20.8
Catchment of the water body in Sławków	44	0.0	0.0	0.0	0.0	20.0	20.0	0.0	60.0	0.1
Catchment of the Kradziejówka water body	45	0.2	1.0	0.0	2.2	6.0	29.9	0.0	64.1	3.5
Catchment of the Lubomia water body	46	3.6	0.8	0.1	1.7	57.0	13.4	1.8	27.8	6.3
Catchment of the Łężczok water body	47	2.4	2.9	8.4	28.6	5.7	6.8	19.8	67.7	42.3
Catchment of the water body in the vicinity of Harmęże	49	1.1	1.2	0.4	5.7	12.8	14.0	5.1	68.1	8.4
Catchment of the Przetok water body	50	0.0	0.1	0.0	0.1	4.2	37.5	0.0	58.3	0.2

Table 2
Lead content in the bottom sediments of water bodies in Southern Poland

Water body name (water body Ref. nos. —see Fig. 1)		Pb [ppm]
Dzierżno Duże	1	124.9
Dzierżno Małe	2	69.5
Pogoria I	3	239.3
Pogoria II	4	454.5
Pogoria III	5	163.0
Chechło	6	498.0
Stawiki	7	1660.0
Morawa	8	2800.0
Hubertus I	9	3125.0
Gliniok	10	2620.0
Hubertus II	11	131.5
Borki	12	1645.0
Borki Małe	13	2340.0
Sosina	14	279.0
Pławniowice	15	33.3
Mały Zalew	16	57.0
Rogoźnik (so-called upper)	17	247.0
Rogoźnik I	18	415.0
Rogoźnik II	19	231.0
Balaton	20	139.0
Czeladź Norwida	21	319.0
Milicyjny	22	34.0
Potok Leśny—water body without name	23	160.0
Kajakowy	24	590.0
Łąka	25	795.0
Ozdobny	26	347.0
Sosnowiec—Kazimierz (Park Leśna)	27	235.0
Gliniok (Western)	28	110.0
Jaworzno (Koparki)	29	164.0
Amendy	30	298.0
Water reservoir in Piekary Śląskie	31	3340.0
Kozłowa Góra	32	474.2
Przeczyce	33	533.0
Paprocany	34	72.5
Żabie doły	35	956.7
Bobrek Flooding	36	568.0
Sosnowiec Klimontów—southern bowl	37	253.0
Sosnowiec Klimontów—eastern bowl	38	410.0
Sosnowiec Klimontów—northern bowl	39	332.0
Zabrze Makoszowy—on the road	40	113.0
Zabrze Makoszowy—in forest	41	32.0
Przy Leśnej	42	2680.0
Pond in the neighbourhood of Przeczyce	43	677.5
Sławków	44	360.0
Żory	45	67.3
Lubomia	46	43.3
Łężczok	47	48.0
Pond in Kuźnica Sulikowska	48	194.0
Pond in the neighbourhood of Harmęże	49	52.0
Przetok	50	465.0

For the purpose of comparing lead concentrations in bottom sediments and in substrate sediments, the anthropogenic enrichment factor of bottom sediments was used (Eq. (2)), which is related to the extent to which the water body studied effectively accumulates matter (this is often equated with contamination). A new indicator (the anthropogenic enrichment factor for bottom sediments) has been proposed, which is expressed by the following formula:

$$I_{\mathrm{AP}} = \frac{C_{\mathrm{BS}}}{C_{\mathrm{SR}}} \tag{2}$$

where I_{AP}—the anthropogenic enrichment factor for bottom sediments (dimensionless number); C_{BS}—the average concentration of the element in question in bottom sediments of the water body; and C_{SR}—the average concentration of the element in question in substrate sediments and in the surroundings of the basin.

The anthropogenic enrichment factor of bottom sediments calculated in this manner has a value below unity if the concentration of the element in sediments is lower than its concentration in the formations in the vicinity of the basin and above unity if the concentration of the element in bottom sediments is higher than that in the vicinity of the basin (the higher the ratio the higher the factor).

3. Study results and discussion

Lead concentrations in bottom sediments of the water bodies studied ranged from 32 ppm (for the Zabrze Makoszowy forest water body) to 3,340 ppm (for the water body adjacent to a mine slag heap in Piekary Śląskie-Brzeziny) (Table 2). The arithmetic mean of all measurements of lead concentrations in bottom sediments amounted to 640 ppm, with a median of 228 ppm and a standard deviation of 888 ppm.

Lead was present in sediments in the vicinity of 20 out of 50 water body basins in concentrations ranging from 15 to 66 ppm. Differences in lead content in sandy formations may be explained by their local distinctive features. Although anthropogenic impact cannot be ruled out, the amounts of lead present in sediments outside water bodies correspond to the geochemical background level accepted for uncontaminated sediments in water bodies in the Upper Silesia region.

The range of lead concentrations (32–3,340 ppm) measured in water bodies in the Upper Silesia region is unlike that found in any studies hitherto conducted worldwide. The above-average pollution levels of the water bodies studied are highlighted by comparisons of the lead concentrations found with the amount of this element found in sediments in other lakes in various parts of the world.

In the sediments of several American lakes in Florida, lead concentrations range from a few to slightly over 100 ppm [14]. Pb concentrations are lower (of the order of a few to around a dozen ppm) in sediments in New Zealand lakes; those attest to anthropogenic pollution in recent decades [15]. Among the lakes compared, there are also water bodies that are subject to agricultural and industrial human impact. These include the African Lake Naivasha, where lead concentrations in sediments do not exceed several dozen ppm [16]. The bottom sediments of Lake Yangzong in China, which is considered to be contaminated by humans, exhibit lead concentrations of up to several dozen ppm [17]. Similar lead concentrations in bottom sediments are found in lakes in the central and lower reaches of the Yangtze River basin [18], and these are barely higher in the sediments of water bodies situated in parks in downtown Shanghai [19]. The sediments of the Australian Lake Illawarra, which lies in the vicinity of large industrial sites, contain no more than several dozen ppm of lead [20]. In around a dozen water bodies in Connecticut, 12–54 ppm of lead were found in the bottom layers of the cores collected (with an average of 30 ppm) and 130–443 ppm Pb were found in top sediment layers (with an average of 310 ppm) [21]. Lead concentration measurements in bottom sediments conducted in 30 Swedish lakes have demonstrated that lead pollution increased gradually during the last two thousand years from a level of a few to a dozen ppm Pb at the beginning of the first millennium CE up to several hundred ppm Pb at the end of the twentieth century [22].

Against the lakes mentioned here, water bodies in the Upper Silesia region appear to be unique in the world in terms of lead concentration in their bottom sediments, since there are no comparable examples worldwide.

Given that the natural concentration of lead in the sediments of surface water bodies in the Silesia and Kraków region established by Lis and Pasieczna [8] is 59 ppm, concentrations that do not exceed this level have been found in seven water bodies (Zabrze Makoszowy—forest, Pławniowice, Milicyjny, Lubomia, Łężczok, Harmęże and Mały Zalew). In the remaining cases, lead concentration in sediments was higher than the aforementioned natural concentration range for this element. For the sediments under consideration, the ratio of the measured values to the geochemical background ranges from 0.5 to 56.6 with an average of 10.8 and a median of 4.9. This indicates that the geochemical background is exceeded at least several times.

The variation in lead concentrations in bottom sediments between individual water bodies, apart from natural factors that are usually related to geological structure, is conditioned primarily by human impact, which is in general reflected by the manner in which the catchment is utilised or by air pollution.

However, the high lead content in the bottom sediments of the water bodies studied cannot be explained by the geological structures of their catchments. Geochemical background for geological formations present on the surface in the region is around 50 ppm Pb, and is usually much higher in ore-bearing Triassic areas [7,8]. The concentration of lead found in sediments in the vicinity of 20 out of 50 water body basins, which ranged from 15 to 66 ppm, was similar to the regional geochemical background for surface geological formations. Neither can high lead concentration be explained by the correlation coefficient calculated for lead content in the bottom sediments of water bodies vs. the share of industrial and urban areas in the total catchment area, which indicates no significant correlation ($-0.5 < \text{corr. coef.} < 0.5$) between these characteristics. Therefore, it can be concluded that local human impact has a strong influence on Pb concentrations. The migration of lead is the result of the dispersion of process waste around pits and smelting centres, which has continued since the Middle Ages. Sometimes, it is simply the result of zinc and lead process waste being transported and stored.

This is clearly illustrated by the example of water bodies situated in the vicinity of areas where non-ferrous metal smelters operate. These are the water bodies with the highest average concentrations of lead in bottom sediments: Piekary-Brzeziny, Hubertus I,

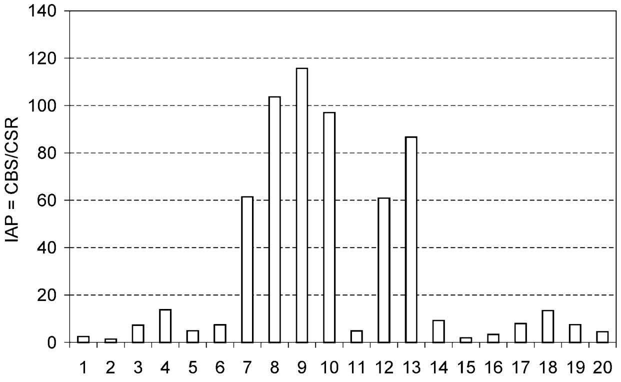

Fig. 3. Anthropogenic enrichment factor values for bottom sediments in flooded mineral workings in the Upper Silesia region (water body designations—see Fig. 1).

Morawa, Gliniok (east), Borki Małe, Stawiki, Borki, Żabie Doły. The Leśna water body, which is situated in a subsidence basin, also stands out with a lead concentration of 2,680 ppm. Basins of such water bodies are in contact with the waste left after processing zinc and lead ores, and their catchments are significantly transformed by human activity, which is evidenced by anthropogenic changes in the surrounding environment. Jankowski et al. [23] mention the presence of a so-called zinc desert in the vicinity of water bodies on the boundary of Sosnowiec and Katowice, which are located near a non-ferrous metal smelter.

In agricultural catchments, which include the areas drained by the Potok Toszecki stream that feeds the Pławniowice water body, and by the Drama River that feeds the Dzierżno Małe water body, lead concentrations in bottom sediments are low and are close to the geochemical background. Equally low concentrations are found in the bottom sediments of water bodies used as fish ponds (Lubomia, Łężczok, a pond near Harmęże, Żory). Similar Pb concentrations were found in water bodies fed from forest catchments: Mały Zalew, Balaton, Makoszowy (forest).

Numerous water bodies exhibit intermediate (compared to the aforementioned extremes) levels of lead pollution, with concentrations in bottom sediments estimated at several hundred ppm. These water bodies are subject to fairly strong anthropogenic impact. However, local conditions play an important role with respect to lead concentrations in bottom sediments.

Sediments in the Dzierżno Duże water body, which is supplied with water by the Kłodnica River with its highly urbanised and industrialised catchment, only contain 124.9 ppm of lead. The Hubertus II water body, which is indirectly included in the manufacturing process taking place at the nearby non-ferrous metal smelter and is known for record high levels of zinc in its sediments (of the order of 30,000 ppm) [23], has a lead concentration of 131.5 ppm. This group also includes most water bodies in flooded sand workings, e.g. the Pogoria and Rogoźnik complexes, Chechło or Sosina. A similar level of lead pollution is exhibited by multi-purpose reservoirs impounded by dams (e.g. Kozłowa Góra, Przeczyce) and some levee ponds that are used for fish breeding purposes. The role of local sedimentary basins, which accumulate lead in concentrations of several hundred ppm, is played by small water bodies in subsidence basins and hollows, which mostly lack drainage.

Conditions may vary depending on the reach studied, as is the case in the Potok Leśny stream catchment. In this catchment, the first water body in the cascade along the stream is not polluted with lead, while each subsequent one exhibits a higher concentration than the previous one (Milicyjny—34 ppm, unnamed water body—160 ppm, Kajakowy—590 ppm, Łąka—795 ppm). This can be explained by, *inter alia*, the supply of pollutants together with rainwater and meltwater from the old (and today fragmentary) road drainage system, and the migration of pollutants from areas where waste from non-ferrous metal smelters is stored [23,24].

Higher lead concentration can be observed in the bottom sediments of water bodies compared to substrate sediments and those in the vicinity of their basins. This is demonstrated by the results of additional tests conducted for several flooded mineral workings. The basins of such water bodies are lined with sandy formations similar to those that are present in the vicinity of old mineral workings and thus the similarity between the sites studied results from the lithological similarity of the material surrounding the basins. This is very important when comparing the contamination levels of bottom sediments, in this case with lead. Samples were collected from sediments representative of the basin substrate and its environment. For the sediments analysed in 20 flooded sand workings, the ratio ranged from 1.4 to 115.7 with an average of 30.8 and a median of 7.7 (Fig. 3). This demonstrates that in bottom sediments, lead was always present at higher concentrations than that in substrate sediments, which ranged from 15 to 66 ppm.

A comparison of lead concentrations in bottom sediments with those in formations in the vicinity of water body basins indicates that a certain environmental protection problem is present. Lead accumulates in bottom sediments in quantities that exceed many times over its normal levels in the area in question. Thus, water bodies fulfil the function of local sedimentary basins in which autochthonous as well as transit (allochthonous) pollutants accumulate.

The accumulation of lead in sediments of sedimentary basins that lack drainage is an environmental problem with both natural and social consequences. It is sufficient to cite the examples mentioned by Jankowski et al. [23] such as the high mortality of tench in the Hubertus water body or the disappearance of eels from the Morawa one—the probable cause of these developments was contamination with heavy metals, including lead.

Local concentration of lead in bottom sediments of flow-through water bodies can be considered a sign that the water is being purified but an environmental problem here is the transport of pollutants along waterways to areas that were not hitherto polluted. A classic example here is the Dzierżno Duże water body, which, despite the fact that it is located outside the boundaries of urban or industrial areas, accumulates pollutants from such areas in its sediments.

4. Conclusions

(1) Lead was found in the bottom sediments of the water bodies examined in amounts ranging from 32 to 3,340 ppm (arithmetic mean—640 ppm, median—228 ppm and standard deviation—888 ppm).

(2) Only in seven out of the 50 water bodies examined did bottom sediments contain lead in amounts that is considered natural; in the remaining water bodies, natural levels were exceeded pointing to anthropogenic pollution. The ratio of the values measured to the geochemical background ranged from 0.5 to 56.6 with an average of 10.8.

(3) In order to confirm the correlation found between the amount of lead in the bottom sediments of water bodies in the Upper Silesia region and the intensity of human impact, additional studies will need to be conducted.

(4) Higher lead concentrations were also found in bottom sediments in comparison to substrate sediments in water body basins, which points to anthropogenic lead enrichment of bottom sediments and thus also to a cumulative impact on water bodies.

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