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TRACE ELEMENTS IN THE BOTTOM SEDIMENTS OF THE IRKUTSK RESERVOIR

PIERWIASTKI ŚLADOWE W OSADACH DENNYCH ZBIORNIKA IRKUCKIEGO

Abstract: The chemical composition of bottom sediments of the Irkutsk Reservoir was examined. Ten sediment samples collected at different depths in four sectors of the Reservoir were analysed in a laboratory. Concentrations of 30 trace elements were determined. The purpose of the study was to assess the anthropogenic impact on the Reservoir geosystem. Barium and zirconium had the highest concentration in the sediments. Concentrations of certain elements varied spatially, while those of others were similar in all the sectors sampled. The highest element concentrations were usually found in sector 3 (in the vicinity of Novogrudinina). Maximum concentrations for around a dozen elements exceeded the geochemical background level for sedimentary rocks and the soil environment. Irkutsk Reservoir sediments exhibited a high concentration of chromium when compared with sediments from various other reservoirs impounded by dams. The study has shown that the environment of the Irkutsk Reservoir is subject to local and regional anthropogenic impact.

Keywords: Irkutsk Reservoir, Lake Baikal, bottom sediments, trace elements, heavy metals

The functioning of water bodies involves the development of morphogenetic processes leading to their terrestrialisation [1–3]. In areas where water bodies are fed by rivers, deltas form [4–6], and in the littoral zone, the material produced by the erosion of shores accumulates [7–9]. At the same time, a layer of sediments forms on the entire bottom of the water body [10–12]. This is a result of sedimentation and sedentation

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processes [13, 14]. Sedimentation is the process whereby material settles out of the water under the influence of gravity. On the other hand, sedentation is the accumulation of organic matter as a result of growth in vegetation within the water body. In reservoirs impounded by dams, bottom sediments mostly form as a result of sedimentation; the waters of the rivers that feed the reservoirs form the primary source of the material accumulated [15–17]. This is confirmed by methods for determining the extent of silting in reservoirs impounded by dams that are based on river flow characteristics [3, 18]. The age of bottom sediments in reservoirs impounded by dams usually does not exceed several decades, so these sediments are not an interesting subject for palaeogeographic studies unlike sediments in natural lakes.

Numerous substances accumulate in bottom sediments. It is often emphasised that these sediments are significant from the point of view of determining the phosphorus cycle; these form the primary environment among the components of the limnic geosystem where this element accumulates [19]. Numerous micropollutants also accumulate in sediments: trace elements (including heavy metals), polycyclic aromatic hydrocarbons, polychlorinated biphenyls, surfactants, radionuclides and others. This is related to the sorption of these pollutants by suspensions within the body of water and their deposition in the sediment material [20]. The presence of micropollutants in bottom sediments is a common subject of study both for natural lakes [21, 22] and anthropogenic water bodies, including particularly those impounded by dams [23, 24]. These studies underline the intensity and nature of anthropogenic impact on the limnic geosystem, since it is mainly human activity that determines the patterns of micropollutant migration and accumulation in the environment [25–28]. In this article, a study is described which examines the presence of trace elements in the bottom sediments of the Irkutsk Reservoir, which is impounded by a dam and fed by the waters of Lake Baikal. The purpose of the study was to determine sediment pollution and to assess the anthropogenic impact on the Irkutsk Reservoir geosystem. The study was also designed to verify the common view that the natural environment in the vicinity of Lake Baikal in the Russian Siberia exhibits low pollution levels. The bottom sediment layer of the Irkutsk Reservoir has already been the subject of studies described in the literature, *eg* with respect to modelling the transport of pollutants [29] or sedimentological zones [30, 31].

The Irkutsk Reservoir, which has operated since 1962, is the highest and at the same time the smallest reservoir of the Angara River cascade [9, 32, 33]. The Reservoir is situated on the upper reach of the Angara River, which flows from Lake Baikal (Fig. 1). It lies within a relatively straight stretch of the valley 55 km in length; its average width is 2 km. The average inflow from Lake Baikal to the Reservoir is 1,850 m^3/s, while the outflow across the dam cross-section is 1,863 m^3/s on average. The reservoir holds around 2.1 km^3 of water. Its average depth is 3.9 m in the upper section, 10.2 m in the middle section and 17.5 m in the section adjacent to the dam. Small towns and villages are situated along Reservoir shores. The city of Irkutsk from which the Reservoir takes its name is located almost entirely below the dam (Fig. 1).

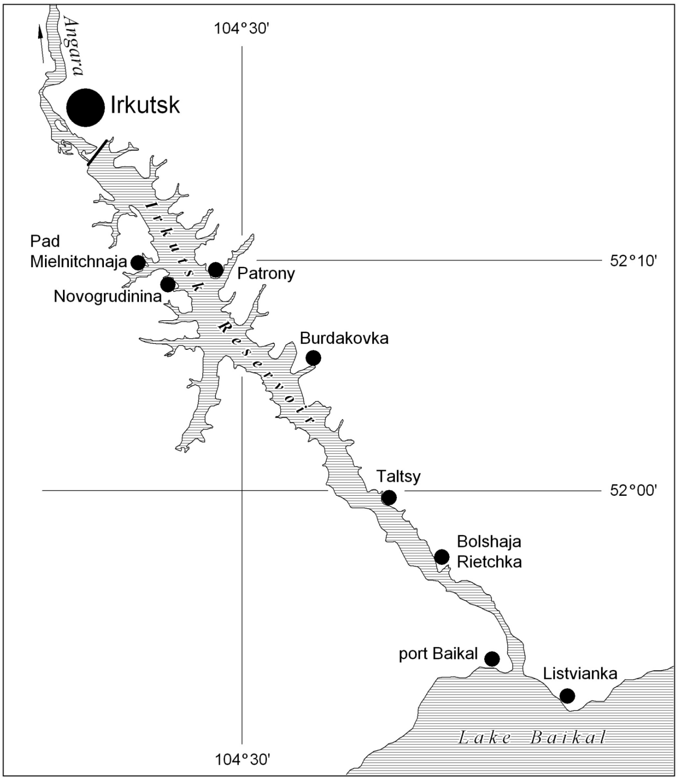

Fig. 1. The location of the Irkutsk Reservoir

Methods

Bottom sediment samples were collected from the Irkutsk Reservoir in July 2010. Samples were collected from a boat, using a sediment core sampler. Ten samples were collected in four Reservoir zones (Table 1):

– zone 1 – in the vicinity of Taltsy;
– zone 2 – in the vicinity of Patrony;
– zone 3 – in the vicinity of Novogrudinina;
– zone 4 – in the vicinity of Pad Mielnitchnaja.

Zone 1 is situated in the upper (southern) part of the Reservoir, while the other zones are in its lower (northern) part.

The sediments collected were placed in sterile plastic containers that were tightly sealed before being delivered to the laboratory. The chemical composition of sediments was analysed at ACTLABS (*Activation Laboratories* Ltd.) in Canada. Analyses were conducted to establish the concentrations of the following trace elements in the samples:

Table 1

Bottom sediment sample collection locations in the Irkutsk Reservoir

Zone	Number of sample	Coordinates		Depth [m]
		latitude	longitude	
1	1	52° 00′ 00.3″ N	104° 39′ 49.7″ E	1.5
	2	51° 59′ 51.9″ N	104° 39′ 44.4″ E	3.0
2	3	52° 09′ 46.4″ N	104° 27′ 22.5″ E	2.0
	4	52° 09′ 38.1″ N	104° 27′ 15.6″ E	1.0
	5	52° 09′ 35.0″ N	104° 27′ 12.4″ E	7.0
3	6	52° 09′ 23.6″ N	104° 25′ 08.7″ E	15.0
	7	52° 08′ 43.7″ N	104° 25′ 18.3″ E	3.5
	8	52° 09′ 12.5″ N	104° 25′ 12.0″ E	0.7
	9	52° 08′ 45.6″ N	104° 25′ 26.3″ E	12.0
4	10	52° 09′ 57.6″ N	104° 22′ 47.6″ E	1.0

Ba, Be, Sr, V, Y, Zr – the FUS-ICP (*fusion-inductively coupled plasma*) method; Cd, Cu, Mo, Ni, Pb, Zn – the TD-ICP (total digestion-inductively coupled plasma) method; Ag, As, Co, Cr, Cs, Hf, Hg, Rb, Sc, Th, U, La, Ce, Lu, Nd, Sm, Eu, Yb – the INAA (*instrumental neutron activation analysis*) method. Element concentrations are given in ppm.

Results and discussion

The sediments examined began to form at the very beginning of the Reservoir's existence. They are a polygenetic material that was supplied by the waters of the main tributary (the Angara), by tributaries within the direct catchment area, from the littoral zone, from the atmosphere (atmospheric deposition) and from the body of water itself (the sedimentation of autochthonous plankton). In the case of the Irkutsk Reservoir, whose catchment exhibits a dispersed human activity pattern, all the sources listed above should be considered responsible for the supply of trace elements. The impact of individual pollution sources on the environment is considered where a certain type of anthropogenic pressure is concentrated and intensive [34–37].

Laboratory analyses determined the presence of numerous trace elements in the bottom sediments examined. Among the 30 elements covered by the study, only silver, cadmium, mercury and molybdenum were not detected (Table 2). The possible concentrations of these elements did not exceed the detection threshold of the method used. The presence of individual elements in the sediment material varied widely. Highest concentrations were recorded for barium (607.3 ppm, *ie* 0.06 % on average) and zirconium (355 ppm, *ie* 0.03–0.04 %). There were also significant amounts of strontium – 233.6 ppm on average (*ca* 0.02 %), chromium – 160 ppm on average (slightly below 0.02 %), vanadium – 123 ppm on average (slightly above 0.01 %), cerium – 103 ppm on average (ca. 0.01 %) and zinc – 84.9 ppm on average (slightly below 0.01 %). Some elements were present in concentrations of at most several parts per million. These were arsenic, beryllium, caesium, europium, samarium, uranium and ytterbium. Lutetium content did not exceed 1 ppm.

Table 2

Presence of trace elements in Irkutsk Reservoir bottom sediments

Element	Zone 1 (samples 1–2)	Zone 2 (samples 3–5)	Zone 3 (samples 6–9)	Zone 4 (sample 10)
	[ppm]			
Ag	< 0.5	< 0.5	< 0.5	< 0.5
As	6–7	7–10	8–9	5
Ba	623–633	595–606	582–615	613
Be	2	2	2	2
Cd	< 0.5	< 0.5	< 0.5	< 0.5
Ce	93–106	85–108	96–151	97
Co	16–17	19–23	18–20	18
Cr	104–123	147–194	148–243	146
Cs	5.7–6.8	3.7–5.3	2.7–5.1	2.8
Cu	21–22	21–34	23–31	22
Eu	1.9–2.3	1.8–2.3	1.7–3.0	1.8
Hf	6.7–7.0	6.3–15.8	7.1–22.9	9.7
Hg	< 1	< 1	< 1	< 1
La	42.7–44.4	47.9–60.0	48.7–75.9	44.6
Lu	0.51–0.58	0.56–0.76	0.53–0.92	0.64
Mo	< 2	< 2	< 2	< 2
Nd	33–45	29–46	35–58	26
Ni	44–48	63–80	60–74	53
Pb	15–16	13–17	15–16	16
Rb	50–90	60–70	40–80	50
Sc	16.0–17.2	17.2–18.9	17.7–18.5	15.5
Sm	5.9–6.4	5.8–7.3	5.8–9.6	5.8
Sr	200–210	186–264	208–274	268
Th	6.7–7.1	7.8–9.9	8.1–12.9	7.1
U	3.4–4.8	2.5–3.3	2.1–4.3	3.4
V	107–108	123–140	124–137	101
Y	27–29	30–38	30–48	34
Yb	3.7–3.8	4.2–5.5	3.9–7.0	4.6
Zn	93–98	73–94	73–93	92
Zr	200–204	200–601	231–863	330

The concentrations of certain elements in the bottom sediments were highly variable depending on where the sample in question was collected. For example, zirconium concentrations ranged from 200 ppm to 863 ppm, while those of hafnium (6.3; 22.9) ppm. On the other hand, certain elements (*eg* cobalt, lead, scandium) were present in similar concentrations in all samples, *ie* their concentrations did not vary spatially (Table 2). This points to the presence of local, anthropogenic sources of selective pollution. For example, study zones Nos. 2 (in the vicinity of Patrony) and 3 (in the vicinity of Novogrudinina) exhibited higher chromium, nickel, vanadium and zirconium concentrations. In general, the highest levels of trace element pollution were found in zone 3, where the maximum concentration for almost half of the elements covered by the study was recorded. Element concentrations in the bottom sediments of zone 4 (the vicinity of Pad Mielnitchnaja) were close to the average for all samples or lower.

The concentrations of the trace elements analysed in the bottom sediments of the Irkutsk Reservoir often exceeded their natural levels in sedimentary rocks or soil (Table 3) [38]. Average concentrations of elements in sediments were higher than the geochemical sedimentary rock background for cerium, chromium, europium, hafnium, scandium and zirconium, while maximum concentrations exceeded the geochemical background for cobalt, neodymium, thorium, uranium, vanadium and ytterbium as well. Natural levels were also exceeded with respect to soil concentrations of the trace elements under consideration. The bottom sediments sampled contained higher levels of around a dozen elements analysed (Ce, Co, Cr, Eu, La, Lu, Nd, Ni, Sc, Sm, Y, Yb) than the natural soil environment. The element concentrations measured in bottom sediments were additionally compared with the legally admissible limits for the surface layer of arable soil in Poland (Table 3) [39]. Those limits were exceeded for barium and chromium while cobalt concentrations oscillated around the admissible value. Thus the bottom sediments analysed could not be used as arable soil in Poland.

The presence of certain trace elements in the bottom sediments of the Irkutsk Reservoir in concentrations higher than those characteristic for the lithosphere and pedosphere points to the presence of anthropogenic impact on the environment of the Reservoir and its catchment. As Karnaukhova [40] states, the waters of Lake Baikal are the main source of trace elements that find their way into the Irkutsk Reservoir. These elements are most probably introduced into water together with the pollutants dumped from the industrial and urban centres located on the southern shores of Lake Baikal as well as with atmospheric deposition. Atmospheric deposition should be considered a major source of trace elements not only in industrial and urban areas but also in the peripheries of urban and industrial centres [41] and even in areas that are situated at a significant distance from pollution sources [42]. The area of southern Lake Baikal and the Irkutsk Reservoir is certainly affected by the influx of pollutants emitted in the nearby Irkutsk–Cheremkhovo Industrial Region and in other industrial centres in the southern part of Eastern Siberia. The supply of trace elements to the Irkutsk Reservoir also occurs within its direct catchment. This is evidenced by the increase in the concentrations of certain elements in the waters of the Angara River during its flow through the Reservoir [40]. It is suspected that the supply of elements is the result not only of the dumping of pollutants from human settlements but also of the chemical denudation of the soil and rock environment.

Table 3

Concentrations of trace elements [ppm] in Irkutsk Reservoir bottom sediments compared with their concentrations in the lithosphere and pedosphere

Element	Irkutsk Reservoir bottom sediments		Sedimentary rocks [38]	Soils [38]	Arable soil [39]
	average value	maximal value	most frequent value	average value	permissible value in Poland
Ag	< 0.5	< 0.5	0.05–0.25	0.03–0.10	—
As	7.7	10	1–13	0.2–16.0	20
Ba	607.3	633	50–800	20–1000	200
Be	2	2	0.2–6.0	0.4–4.3	—
Cd	< 0.5	< 0.5	0.035–0.300	0.20–1.05	4
Ce	103	151	7–90	48.7	—
Co	19	23	0.1–20.0	8	20
Cr	160	243	5–120	7–150	150
Cs	4.5	6.8	0.5–10.0	0.1–26.0	—
Cu	26.4	34	2–60	1–140	150
Eu	2.1	3	0.2–2.0	1.23	—
Hf	10	22.9	0.3–6.0	21[1]	—
Hg	< 1	< 1	0.04–0.40	0.05–0.30	2
La	52	75.9	4–90	26.1	—
Lu	0.6	0.92	0.2–1.2	0.34	—
Mo	< 2	< 2	0.14–2.60	0.7–4.0	10
Nd	39	58	4.7–41.0	19.5	—
Ni	62.3	80	5–90	6[2]	100
Pb	15.3	17	3–40	25–40	100
Rb	65	90	5–200	lack of data	—
Sc	18	18.9	0.5–15.0	2–12	—
Sm	6.5	9.6	1.3–10.0	4.8	—
Sr	233.6	274	20–600	5–1000	—
Th	8.6	12.9	1.7–12.0	6–13	—
U	3.4	4.8	0.45–4.10	1–11	—
V	123	140	10–130	11–220	—
Y	33	48	4–50	5–25	—
Yb	4.6	7	0.3–4.4	2.06	—
Zn	84.9	98	10–120	30–125	300
Zr	355	863	20–220	470[1]	—

[1] in loess soil in Russia; [2] in agricultural soil in Poland.

While analysing the presence of trace elements in the bottom sediments of the Irkutsk Reservoir, special attention should be paid to heavy metal concentrations. The presence of heavy metals best reflects the extent of anthropogenic impact, since they are introduced into the aquatic environment chiefly as a result of human activity owing to their widespread use in industry [20, 43, 44]. In Table 4, concentrations of cadmium, lead, copper, zinc, chromium and nickel in the bottom sediments of the Irkutsk Reservoir and of other reservoirs impounded by dams in other part of the world are listed [45–59].

Table 4

Heavy metal concentrations in bottom sediments of selected reservoirs impounded by dams worldwide

Reservoir	Cd	Pb	Cu	Zn	Cr	Ni
	[ppm]					
Atatürk Dam Lake (Turkey) [45]	—	—	15–23	59–61	—	44–140
Barra Bonita (Brazil) [46]	5.0–6.9	43–71	166–255	224–230	75–168	98–107
Billings Reservoir (Brazil) [47]	59 ± 8	438 ± 33	562 ± 35	1640 ± 114	802 ± 66	432 ± 41
Dillon Reservoir (USA) [48]	5–13	64–299	31–195	912–3217	—	7–51
Irkutsk Reservoir (Russia)	**< 0.5**	**13–17**	**21–34**	**73–98**	**104–243**	**44–80**
Ivankovo Reservoir (Russia) [49]	—	9–28	11–111	55–540	48–165	15–43
J.A. Alzate Reservoir (Mexico) [50]	2.0–2.8	12–76	15–61	92–233	< 50–145	15–43
Keban Dam Lake (Turkey) [51]	—	—	912–5398	1226–6592	1364–31264	833–7902
Kuibyshev Reservoir (Russia) [52]	—	26–40	42–59	100–220	—	67–180
Nasser Lake (Sudan/Egypt) [53]	3–11	12–29	9–69	30–97	5–50	92–145
Rybnik Reservoir (Poland) [54]	2–85	11–315	16–1117	51–2441	14–739	3–184
Temple (France) [55]	0.6–180	31.3–593	16.7–78	82–7230	—	—
Texoma Lake (USA) [56]	1–3	5–15	9–136	33–242	12–51	6–31
Tresna (Poland) [57]	0.0–1.7	25–62	16–36	83–177	12–56	31–66
Tuttle Creek Lake (USA) [58]	0.3–0.6	16–160	20–44	65–150	48–120	19–77
Wadi Al-Arab Dam (Jordan) [59]	6–13	—	20–190	170–960	—	—

These data show that compared with other reservoirs, small amounts of cadmium, lead, copper and zinc are present in the sediments of the Irkutsk Reservoir. Nickel concentrations in the sediments of the Irkutsk Reservoir are comparable with the levels recorded for many other reservoirs; it is only chromium concentrations in the sediments that are high in the Irkutsk Reservoir compared with other such reservoirs. Sources of chromium in the aquatic environment include effluent from many sectors of industry, domestic sewage and burning coal. Therefore, the environment of the Irkutsk Reservoir is subject to anthropogenic impact that is reflected, *inter alia,* by high chromium concentrations. The only positive aspect of this pollution pattern is the fact that chromium exhibits the lowest toxicity among the heavy metals listed and does not accumulate in aquatic organisms [44].

Conclusions

1. The operation of the Irkutsk Reservoir for almost half a century has resulted in the formation of the bottom sediment layer.
2. The sediments contained numerous trace elements, chief among which were barium and zirconium. The concentrations of certain elements (*eg* zirconium, hafnium) were similar for different Reservoir zones, while the presence of others (*eg* cobalt, lead) varied spatially to a significant extent.
3. Around a dozen elements were present in the bottom sediments examined in quantities that exceeded their natural concentrations in sedimentary rocks and in the soil environment.
4. Compared with sediments in other reservoirs impounded by dams, sediments of the Irkutsk Reservoir exhibited both high chromium concentrations and at the same time low cadmium, lead, copper and zinc concentrations.
5. The presence of trace elements in the sediments of the Irkutsk Reservoir points to the existence of local and regional anthropogenic impact on the environment of the Baikal area.

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PIERWIASTKI ŚLADOWE W OSADACH DENNYCH ZBIORNIKA IRKUCKIEGO

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Abstrakt: Badano skład chemiczny osadów dennych Zbiornika Irkuckiego. W laboratorium przeanalizowano 10 próbek osadów, pobranych w czterech sektorach zbiornika z różnych głębokości. Określono zawartość 30 pierwiastków śladowych. Celem badań była ocena wpływów antropogennych na geosystem zbiornika. W składzie osadów dominowały bar i cyrkon. Koncentracja niektórych pierwiastków była zróżnicowana przestrzennie, a innych zbliżona we wszystkich sektorach badawczych. Największe zawartości pierwiastków występowały najczęściej w sektorze 3 (w rejonie miejscowości Nowogrudinina). Maksymalne zawartości kilkunastu pierwiastków przekraczały poziom tła geochemicznego dla skał osadowych i środowiska glebowego. Na tle osadów różnych zbiorników zaporowych osady Zbiornika Irkuckiego wyróżniała duża zawartość chromu. Badania wykazały, że środowisko Zbiornika Irkuckiego podlega lokalnym oraz regionalnym wpływom antropogennym.

Słowa kluczowe: Zbiornik Irkucki, jezioro Bajkał, osady denne, pierwiastki śladowe, metale ciężkie