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Preliminary assessment of silting and the quality of bottom sediments in a small water reservoir

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Abstract

The aim of this study was to assess the degree of silting and pollution of bottom sediments in a small water reservoir Lubianka situated in Starachowice, Świętokrzyskie Province, with selected heavy metals (Pb, Cr, Cd, Cu, Ni, Zn, Fe, Mn, Hg). Catchment basin of the reservoir is forested in 92%. Other parts are covered by estates of detached houses, barren lands and green areas. Bathymetric measurements and analyses of trace elements in bottom sediments were made in 2012. After 28 years of exploitation, reservoir's basin accumulated 43 thousand cubic metres of sediments i.e. 4.7% of its initial volume. Mean annual silting rate was 0.17%. Due to the content of copper and chromium, bottom sediments were classified to the II category (sediments of average pollution) according to geochemical standards. Concentrations of Pb, Cd and Hg in all analysed samples were below geochemical background. In a sample collected at the inlet to the reservoir, the TEL index for chromium was exceeded by 25.6%. In other samples the threshold values of the TEL and PEL indices were not exceeded.

Key words: *heavy metals, silting, small water reservoir*

INTRODUCTION

Water reservoirs are being silted. Material from surface denudation, including the erosion of riverbed, is deposited in their basins. The highest rate of shallowing is observed in small dam reservoirs [BĄK, DĄBKOWSKI 2013; DĄBKOWSKI *et al*. 1982; MICHALEC 2008]. Based on a study of 20 small reservoirs in the catchment basin of the Rio Grande of an area from 20 thousand to 1200 thousand m^3, Dendy [after MICHALEC 2012] found that the mean rate of silting of these reservoirs ranged from 0.6 to 4.5%. BATUCA and JORDAAN [2000] noted that four Austrian reservoirs of a volume of 200 thousand to 2100 thousand m^3 lost annually from 0.5 to 2.5% of their volume on average. According to MICHALEC [2008], mean rate of silting of small water reservoirs situated in the catchment basin of the upper Vistula River was 2.36%. Substantial loss of volume may limit reservoirs' functions and make their proper exploitation impossible. Hence, the need arises for their de-silting. Potential management of extracted bottom sediments depends on their physical and chemical properties [MADEYSKI, TARNAWSKI 2007] and on the presence of pathogenic microorganisms [GAŁKA 2010]. Chemical composition of sediments depends largely on human activity in the catchment basin. Trace elements reach surface waters in industrial and municipal sewage and storm waters and in the surface runoff from roads, fields and meadows [NOCOŃ *et al*. 2013; STAMATIS *et al*. 2002]. Heavy metals may also originate in shallow mineral deposits.

Heavy metals delivered to reservoirs with river waters may be immobilised in sediments for a long period of time due to sedimentation and sorption [BARBUSIŃSKI, NOCOŃ 2011; BĄK *et al*. 2013]. It is important that they do not undergo biodegradation but only biotransformation. Uncontrolled input of heavy metals to aquatic environment is particularly dangerous because of their persistence and ability to accumulate in living organisms (plants, animals) even if delivered periodically in small amounts. Analyses of heavy metal content in bottom sediments is important since they may be a source of information on geochemical situation in the catchment basin and on the character of aquatic environment.

Determination of the quality of sediments and their environmental impact is often performed by a comparison of the content of harmful substances with threshold values. The order of the Minister of Environment of 9th September 2002 [Rozporządzenie MŚ… 2002] established allowable concentrations of harmful substances in soil or earth. Ecological assessment of aquatic sediments may also be performed based on geochemical criteria. Then, the results are referred to geochemical background i.e. to the natural conditions devoid of human impact [BOJAKOWSKA, SOKOŁOWSKA 1998].

Having in mind a tremendous environmental impact of harmful substances accumulated in bottom sediments, results of analyses are more and more often referred to eco-toxicological parameters which determine the effect of pollutants on organisms living in aquatic habitats. Threshold effects level (TEL) sets the upper limit of contaminant concentration, below which a negative effect on aquatic organisms is rare. Probable effects level (PEL) is defined as the lower range of pollutant concentrations, which may exert remarkable negative effect on living organisms [MACDONALD *et al*. 2000].

The aim of this study was to assess the silting rate and the degree of pollution by trace elements (Pb, Cr, Cd, Cu, Ni, Zn, Fe, Mn, Hg) of bottom sediments in Lubianka Reservoir after 28 years of its exploitation. The country geochemical standards and ecotoxicological indices PEL and TEL were used to assess the effect of sediments on the aquatic environment.

MATERIAL AND METHODS

STUDY OBJECT

Water reservoir Lubianka is situated on the river of the same name. The Lubianka River is a right tributary of the Kamienna River. Its springs are located at an elevation of 319 m a.s.l. in southern part of the Sieradowice Landscape Park near Nowa Wieś. The river flows through Wzgórza Koneckie built of Triassic formations 700 m thick. These formations consist of grey and red sandstones interspaced by clays. Above the Triassic formations there are Quaternary fluvio-glacial sands and morainic loams. Holocene deposits – sands and organic alluvia – occupy locally the bottom of the Lubianka River valley [KOSTERA, JAWORSKI 1975]. The Lubianka drains an area of 57.10 km^2 and its total length is 16.50 km. Longitudinal inclinations of the river bed range from 3 to 10‰.

Total projected volume of the reservoir exploited since the 1980s is 896 thousand m^3. Based on the analysis of documentation [KOSTERA *et al*. 1975; 1986a, b], own measurements and discussions with local authorities we found, however, that the reservoir was not constructed according to the project. Moreover, northern part of the reservoir along Południowa Street was with time adopted for recreational purposes, which was associated with a change in natural topography of the bottom in a 20 m wide shore belt. Constructors resigned from building an island of an area of 1500 m^2 which was primarily planned near the left shore some 220 m from the dam. Designed embankments were also abandoned, which moved flooding range along Północna Street from several to several tens of metres at NPP (Normal Water Level) equal 222.00 m a.s.l. A digital model of the reservoir, which considered all changes mentioned above, was created to estimate primary reservoir's volume. Performed calculations showed that the primary volume was ca. 906 thousand m^3.

Now the depth of reservoir varies from 0.5 to 7 m and flooded area at NPP is 30 ha. Dam of a length of 160 m is situated in 4.7 km of the river course and closes partial catchment basin of an area of 35.15 km^2. The reservoir is equipped with a permanent spillway and bottom sink. Permanent spillway is 25 m long and shaped in a semicircle with the radius of 8.0 m. Bottom sink is made of two steel pipes 45 m long and 500 mm in diameter. One of them serves as an emergency outflow [KOSTERA *et al.* 1975].

Reservoir's bottom and adjacent areas are built of sands underlined by clay and loam. Catchment basin is in 92% covered with forest, fir and pine being the dominating species. The remaining grounds are occupied by estates of detached houses, barren lands and green areas.

Annual mean precipitation in the catchment basin is 613 mm. The biggest monthly mean precipitations occur in July and August, the smallest – in January, February and March. Characteristic flows of a given probability for a cross-section closed by dam are presented in Table 1 [KOSTERA, JAWORSKI 1975].

Table 1. Characteristic water flows in the Lubianka River (area of the catchment basin – 37.6 km^2)

$Q_{p\%}$, m^3·s^{-1}							Characteristic flows	
0.1	0.5	1.0	10	20	50	100	Q_{SW}	Q_{NT}
95.0	70.0	61.4	29.3	20.0	8.3	0.92	0.286	0.182

Source: own elaboration based on: KOSTERA and JAWORSKI [1975].

METHODS

Bathymetric measurements were made in June 2012 from a boat equipped with the integrated system for depth and location measurements (two-channel echo sounder EA400 SIMRAD and GPS receiver Trimble SPS351). To increase accuracy and eliminate possible errors, sounding was performed at a frequency of 3 records per second. Position, geographic longitude and latitude measured with the accuracy of 0.001 sec. were attributed to each depth. Echo sounding gave a set of points covering the reservoir at water depths greater than 0.6 m. Zones of smaller depths, not covered by echo sounding, were determined from flood ranges taken from plane images. So obtained data served to elaboration of the reservoir's bathymetric map with isobaths drawn every meter and to estimate its volume with the use of SURFER 11 software. The accuracy of applied system was: depth measurement ±0.5%, particular depth ±1 cm, boat location ±0.5 m. Echo sounder route during measurements is presented in Fig. 1.

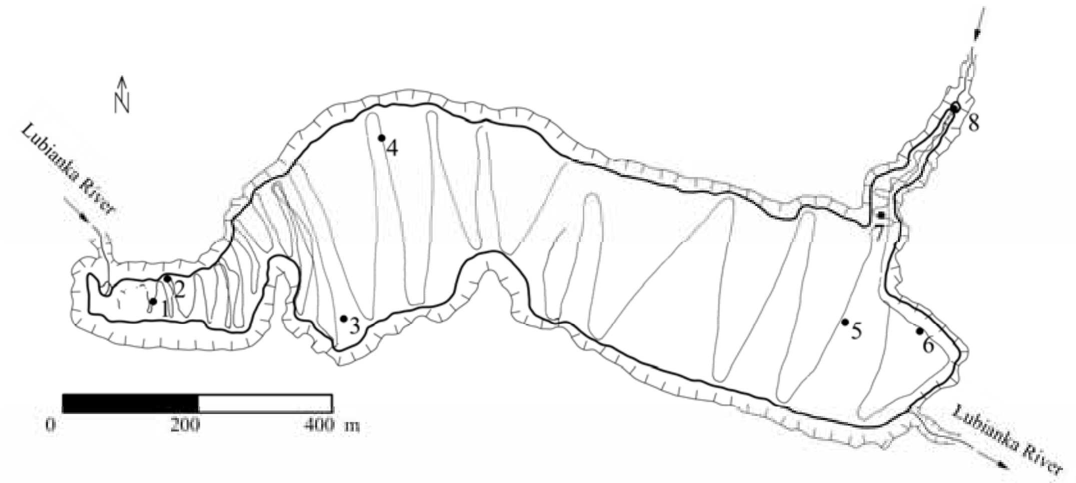

Fig. 1. Bottom sediment sampling sites and routes of echo sounder during depth measurements; source: own elaboration

Silting rate S_z in the reservoir expressed in percent was calculated as a ratio of particulate matter retained in reservoir V_z to its initial volume V_p:

$$S_z = \frac{V_z}{V_p} \cdot 100\% \qquad (1)$$

Samples of bottom sediments for the determination of heavy metals were collected during measurements of silting. Sediments were collected to transparent cylinders of internal diameter 57 mm and length 1200 mm with the „Becker" type sampler. The sampler is equipped with a device that allows closing the cylinder and collecting undisturbed sediment samples. Sampling sites are presented in Fig. 1. In the laboratory, collected samples were dried at 60°C, ground to grain size smaller than 0.063 mm and mineralized. Total concentration of Pb, Cr, Cd, Cu, Ni, Zn, Fe, Mn, Hg was determined in the upper 10 cm sediment layer. Depending on concentrations, measurements were performed with atomic absorption spectrophotometry using SavantAA Sigma or SavantAA Zeeman spectrophotometers. Organic matter content was determined as a loss on ignition at 550°C acc. to PN-EN 12880:2004.

Pollution of bottom sediments was assessed with the use of geochemical criterion. The criterion distinguished three classes of pollution (Tab. 2), for which a threshold value is a multiplier of the background value and abnormal content is defined as a concentration higher by two standard deviations than the mean of a given population [BOJAKOWSKA, SOKOŁOWSKA 1998]. Potential effect of pollutants on aquatic ecosystems was evaluated using PEL and TEL indices (Tab. 2) [MACDONALD *et al*. 2000].

Organic particles from sediments may absorb heavy metals [KYZIOŁ 1994; MADEYSKI, TARNAWSKI 2006]. Therefore, an attempt was undertaken to calculate the relationship between the content of organic matter and concentrations of heavy metals in sediments. Pearson correlation coefficient (r_p) at $p < 0.05$ was used for this purpose. To verify null hypothesis H_0: $r_p = 0$, t statistics was used in a form:

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \qquad (2)$$

where:
r – Pearson correlation coefficient,
n – number of samples.

As shown by Fisher [VOLK 1973] this statistics has Studenta t distribution with $n - 2$ degrees of freedom. Normal distribution of analysed variables was tested with Shapiro-Wilk W test. If the distribution deviated from normal, variables were log-transformed [CHUCHRO 2011]. The indices of pollution were also

Table 2. Permissible concentration of heavy metals in bottom sediments

Chemical elements	Geochemical criterion				PEL	TEL
	geochemical background	class I – poorly contaminated sediments	class II – moderately contaminated sediments	class III – contaminated sediments		
	mg·kg^{-1}					
Cadmium (Cd)	<0.5	<1.0	<5	<20	3.53	0.596
Chromium (Cr)	5	<20	<100	<500	90	37.3
Copper (Cu)	6	<20	<100	<200	197	35.7
Mercury (Hg)	<0.05	<0.1	<0.5	<1.0	0.486	0.174
Nickel (Ni)	5	<30	<50	<100	36	18
Lead (Pb)	10	<50	<200	<500	91.3	35
Zinc (Zn)	48	<200	<1000	<2000	315	123

Source: own elaboration based on: BOJAKOWSKA and SOKOŁOWSKA [1998], MACDONALD *et al*. [2000].

characterised by the central value (arithmetic mean $\bar{x}$) and a measure of variability (variability coefficient V) and clustered acc. to the Ward's method. The analysis of variance was used to estimate the distance among clusters. The analysis aims at minimizing the sum of squares of deviations of any two clusters which may be formed at each step of agglomeration [GRAJEWSKI 2006].

RESULTS AND DISCUSSION

Volume of Lubianka Reservoir after 28 years of its exploitation is 863 thousand m^3. At 906 thousand m^3 initial volume one may find that 43 thousand m^3 of sediments were deposited in water basin i.e. 4.7% of initial volume. Mean annual silting rate was thus 0.17%. About 17% of total sediment volume deposited in the upper part of reservoir whose volume constitutes about 2% of the total volume. Sediments settling at the Lubianka River inlet formed a delta cut by numerous branches of the main channel within which sediment thickness exceeded 50 cm in many places. Experimental studies carried out by MARTENS [1986] showed that this is a „mature" form characteristic for the third (last) phase describing sediment deposition at the inlet to the basin.

Low silting rate of Lubianka Reservoir may result from its large volume and land use. The reservoir is characterised by the volume coefficient (the quotient of reservoir's volume and annual mean volume of inflowing water) equal 9.52%. With reference to volume coefficient, the reservoir may be classified to the group of medium size reservoirs with small sediment increments [TARNAWSKI, MICHALEC 2006].

Table 3 shows results of heavy metal analyses in bottom sediment of Lubianka Reservoir. The highest variability of results was noted for iron, chromium, nickel, lead and cadmium. The highest concentrations of these metals were found in samples collected near northern shore of the water body (samples 2, 4 and 8). Noteworthy is the sample no. 8 collected near the inlet of the left inflow to reservoir. The inflow is 1200 m long and drains water from neighbouring barren lands and detached houses. Bottom sediments from this part of reservoir had highest content of Cr, Zn, Ni, Cu and Pb. Also concentrations of Mn and Cd were ones of the highest. Probably storm waters drained from paved roads exert the biggest impact on the quality of sediments deposited in this part of reservoir.

Copper concentrations were least variable among all samples (Tab. 3) and did not exceed 35.1 mg·kg^{-1}. Mercury concentrations varied between 0.001 and 0.002 mg·kg^{-1} and in samples 1, 3, 7 and 8 were below the detection limit.

Table 3. Heavy metal content in bottom sediments of Lubianka Reservoir

Sample number	Fe	Cr	Zn	Ni	Mn	Cu	Pb	Cd	Hg	Organic matter content, %
	mg·kg^{-1}									
1	189	35.1	48.3	5.22	682	34.0	2.96	0.18	–	26.1
2	432	32.6	55.2	3.78	727	27.9	2.13	0.33	0.002	24.1
3	195	22.6	52.9	5.18	673	30.1	4.78	0.24	–	4.2
4	485	28.4	55.3	4.99	783	32.1	4.55	0.18	0.001	1.2
5	359	23.2	50.0	2.93	496	29.0	2.06	0.31	0.001	2.2
6	412	30.0	62.7	3.15	755	26.9	3.74	0.11	0.001	2.9
7	420	18.2	68.3	2.77	596	28.9	1.49	0.26	–	0.8
8	251	46.8	74.1	5.79	635	35.1	4.90	0.32	–	0.8
$\bar{x}$	342	29.6	58.3	4.22	668	30.5	3.32	0.24	–	7.78
V	33.6	30.1	15.6	28.3	13.8	9.65	40.6	32.8	–	138

Explanations: $\bar{x}$ – arithmetic mean, V – coefficient of variation.
Source: own elaboration.

Relationships between organic matter and heavy metal concentrations were weak or very weak (correlation coefficients between –0.28 and 0.34). The relationship was strong only for zinc (r_p = –0.66). However, all correlation coefficients were insignificant at p = 0.05. Examples of correlations for Zn and Cd are shown in Fig. 2.

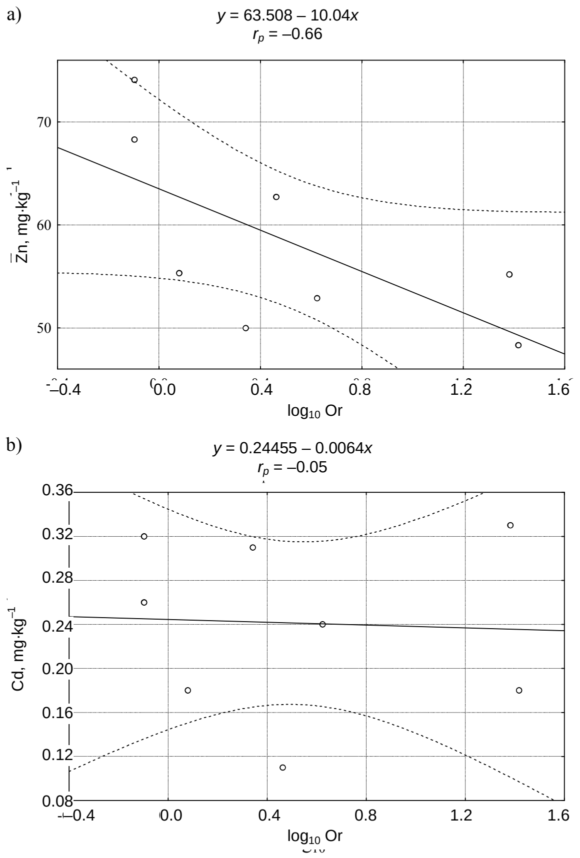

Fig. 2. The regression of Zn (a) and Cd (b) concentration on organic matter content; source: own elaboration

Preliminary assessment of data structure was made with cluster analysis using the Ward's method. Two three-element clusters (points 1, 3 and 8 and 2, 4 and 6) and one two-element cluster (points 5 and 7) are clearly seen in the dendrograph (Fig. 3) at a distance of 120. Elements most important for the affiliation to particular clusters were the concentration of: iron (F = 30.5421, p < 0.0015), manganese (F = 16.8121, p < 0.0060) and nickel (F = 10.1397, p < 0.0173).

Based on geochemical criteria, bottom sediments of Lubianka Reservoir may be classified as moderately contaminated by copper (samples 1–8) and chromium (samples 1–6 and 8). Poorly contaminated were samples 1, 3 and 8 (by nickel), 1–8 (by zinc) and 7 (by chromium). In other cases, the concentrations of trace elements were below geochemical background.

Indices PEL and TEL were used to assess the effect of pollutants accumulated in bottom sediments on aquatic ecosystem functioning. According to criteria of this method, only chromium exceeded the threshold value by 25.6% in sediments from site 8. Threshold or probable values of analysed contaminants were not exceeded in other samples.

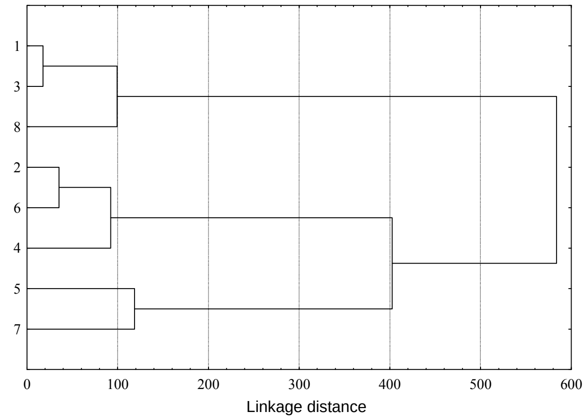

Fig. 3. Agglomeration using the Ward method; source: own elaboration

CONCLUSIONS

The following conclusions can be drawn from quantitative and qualitative analyses of bottom sediments in Lubianka Reservoir:

1. The reservoir shows low intensity of silting. After 28 years of exploitation 43 thousand m^3 of bottom sediments i.e. 4.7% of initial volume were deposited in reservoir's basin. Mean annual rate of silting was 0.17%.
2. Bottom sediments deposited in the upper part of reservoir had high content of organic matted exceeding 24%. In other samples collected from the middle part and near the dam, organic matter content did not exceed 4.2%.
3. According to geochemical standards, bottom sediments in Lubianka Reservoir may be classified as moderately contaminated due to elevated concentrations of chromium and copper.
4. Chromium concentration in sediments collected near the inlet of left tributary fed with storm waters exceeded the threshold environmentally safe value by 25.6%.

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Wstępna ocena stopnia zamulenia i jakości osadów dennych małego zbiornika wodnego

STRESZCZENIE

Słowa kluczowe: *mały zbiornik wodny, metale ciężkie, zamulenie*

Celem pracy była ocena stopnia zamulenia oraz zanieczyszczenia osadów dennych małego zbiornika wodnego Lubianka wybranymi metalami ciężkimi (Pb, Cr, Cd, Cu, Ni, Zn, Fe, Mn, Hg). Zbiornik jest położony w miejscowości Starachowice w woj. świętokrzyskim,. Zlewnia zbiornika w przeszło 92% pokryta jest lasami. Pozostałą część stanowią osiedla domków jednorodzinnych, nieużytki rolne i tereny zielone. Pomiary batymetryczne oraz badania zawartości pierwiastków śladowych w osadach dennych wykonano w 2012 r. Na podstawie ich analizy stwierdzono, że po 28 latach eksploatacji w czaszy zbiornika odłożyło się 43 tys. m^3 osadów. Stanowi to 4,7% jego pierwotnej pojemności. Roczny stopień zamulenia obiektu wynosi średnio 0,17%. Ze względu na zawartość miedzi i chromu osady denne zbiornika zaklasyfikowano do II kategorii według standardów geochemicznych (osady miernie zanieczyszczone). Zawartość ołowiu, kadmu i rtęci we wszystkich analizowanych próbkach była mniejsza od tła geochemicznego. W próbie osadów pobranej u wlotu dopływu do zbiornika stwierdzono przekroczenie wartości wskaźnika TEL dla chromu, które wyniosło 25,6% wartości progowej. W pozostałych próbach nie stwierdzono przekroczeń wartości progowych wskaźników TEL i PEL.