ECOLOGICAL AND HUMAN HEALTH RISKS ASSESSMENT OF HEAVY METALS IN BOTTOM SEDIMENTS OF THE PŁAWNIOWICE WATER RESERVOIR – ARTIFICIAL LAKE (SILESIAN VOIVODESHIP, POLAND)

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Abstract

This study aimed to assess the ecological and human health risks of heavy metals (Cd, Cr, Cu, Ni, Pb, and Zn) in the bottom sediments of the Pławniowice reservoir, which is located in the Silesian Voivodeship, one of the most polluted regions in Poland. Sediment samples were collected at 5 sampling points located along the main axis of the reservoir. The concentrations of heavy metals were determined using Avio 200 ICP-OES atomic absorption spectrometer (PerkinElmer Inc.). The geochemical quality classification, Geoaccumulation Index (I_{geo}), Ecotoxicological criteria, and Potential Ecological Risk Factor (ER) were used for the assessment of the ecological risk, while for the human health risks, the Hazard Quotient (HQ), Hazard Index (HI), Carcinogenic Risk (CR) and Total Carcinogenic Risk (TCR). The results of the ecological risk analysis indicated that among the studied metals, only Cd may pose a potential hazard to the fauna and flora of the reservoir. The results of the health risks assessment indicated that the primary exposure pathway for adults and children can be accidental ingestion of polluted sediments. In both cases, children are far more exposed to the health effects. Although the studied metals did not pose a direct threat to human health, due to the values of CRs and TCRs to Cd, Cr and Ni it is recommended to take appropriate steps to reduce the concentrations of these heavy metals in the bottom sediments by their periodical removal.

Keywords: bottom sediments, heavy metals, ecological risk, human health risk, artificial water reservoir

1. Introduction

Bottom sediments are integral to all aquatic ecosystems. They are typically formed through a combination of processes, including the sedimentation of mineral and

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organic particles derived from erosion and precipitation of various components from the water (Świercz, Tomczyk-Wydrych, Bąk, 2022). Moreover, sediments provide a substrate and a habitat for various aquatic organisms and are involved in biogeochemical processes. They are also a place of deposition and transformation of numerous compounds, e.g., nutrients, metals, etc. (Siebielec, Siebielec, Smreczak, 2015; Świercz, Tomczyk-Wydrych, Bąk, 2022). Some of the pollutants that become accumulated in bottom sediments, such as heavy metals, may have a negative impact on the aquatic environment (Pohl et al., 2022). Metals can pose significant risks to aquatic ecosystems and human health due to their toxicity, environmental persistence and ability to bioaccumulate in the food chain (Jiménez-Oyola et al., 2021; Şimşek, Özkoç, Bakan, 2022). Therefore, the pollution of water reservoirs with heavy metals is a problem on a global scale.

The chemical composition of bottom sediments mainly depends on human activity, which affects the geochemical situation of the catchment. The main sources of metal pollution of aquatic ecosystems comprise wastewater (municipal and industrial), mining, mineral processing industry, surface runoff from fields and roads and atmospheric deposition. To a much lesser extent, these elements come from natural sources, among which the following can be distinguished: rock weathering processes and soil erosion (Tytła, Kostecki, 2019; Şimşek, Özkoç, Bakan, 2022).

According to the Act of 14 December 2012 on waste (Polish Journal of Laws/ Dz.U.2013, Item 21), sediments (dredging spoil) extracted from the bottom of a water reservoir are considered as waste and classified as a material suitable for repeated placement in the environment without restrictions, or as a contaminated material intended for storage at hazardous waste landfills. The final decision is made based on their chemical composition.

The assessment of the chemical quality of bottom sediments largely determines the condition of aquatic ecosystems and serves as a basis for the development of a management system strategy for this environment component (Tytła, Kernert, 2021). However, this requires a multi-faceted approach. Evaluating potential ecological and human health risks associated with metals is crucial for understanding the environmental impact and potential hazards. This is especially important in the case of artificial water reservoirs that have been created as a result of human activity. In Poland, many of these types of water reservoirs are located in the Silesian Voivodeship, one of the most polluted regions in the country, and even in Europe (Tytła, Kostecki, 2019).

The main objective of the research was to assess the ecological and human health risks associated with the presence of heavy metals (Cd, Cr, Cu, Ni, Pb, and Zn) in the bottom sediments of the Pławniowice water reservoir, an artificial lake. There are only few works concerning both the ecological and human health risks assessment of heavy metals in the bottom sediments of water reservoirs in Poland, which confirms the innovative character of the presented study.

2. Materials and methods

2.1. Material and study area

The research material comprised bottom sediments collected from the Pławniowice water reservoir (also called "lake"). Samples were collected at five measuring points, which were located along the main axis of the reservoir, from a depth of 10 m to 15 m, i.e., S1 (10 m), S2 (14 m), S3 (12 m), S4 (14 m) and S5 (15 m). For the sample collection, the Birge-Ekman sampler (Wildco, USA) was used. The thickness of the sediment layer was 5 cm. All sediment samples were collected in 2022.

The Pławniowice water reservoir is located in the central part of the Silesian Voivodeship, in the southwestern part of Poland (50°23'22"N, 18°28'24"E), a few kilometres from its western border (Gliwice County, Rudziniec commune). It was created in the excavation site after discontinuance of the exploitation of backfill sands, in the 1970s. The reservoir is situated in the catchment area of the Toszecki Stream, which flows into the Kłodnica River (right tributary of the Odra River) (Machowski, Rzętała, 2015; Machowski, Rzętała, 2018). Pławniowice, together with the Dzierżno Małe, Dzierżno Duże reservoirs, and the Gliwice Canal, form the so-called the Western Hydrotechnical System of the Upper Silesian Industrial District, also known as the Hydrotechnical System of the Kłodnica River, which constitutes a water reserve for the Gliwice Canal and a source of industrial water (Kostecki, Suschka 2013; Tytła, Kostecki, 2019). The Pławniowice reservoir is intended mainly for industrial, flood control and recreational purposes. The surface of the water table is 225 ha, the volume of the reservoir is 29 million m^3, and the maximum depth is 16 m. The catchment area of the reservoir is 121.79 km^2, it is mainly agricultural land (69%) and forest (24%), the rest is built-up land (3%), communication areas (2%), flowing and stagnant waters (2%) (Kostecki, Suschka, 2013; Pohl, Kostecki, 2020). Moreover, the reservoir is situated between the A4 motorway (in the south) and the national road No DK40 (in the north). The location of the study area and the sampling points are shown in Figure 1.

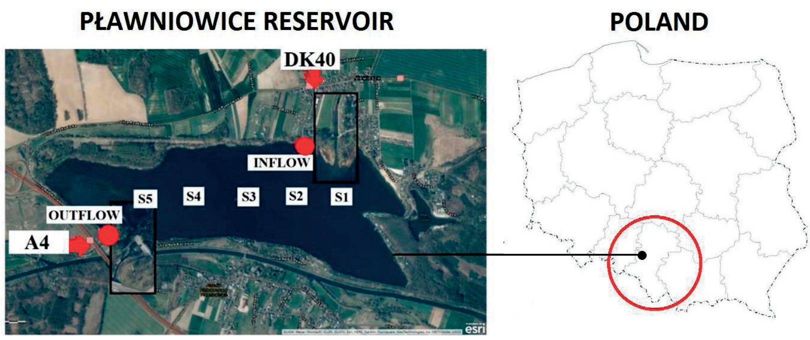

Figure 1. Location of the Pławniowice reservoir and sampling points
Source: Based on the (https://www.arcgis.com/home/webmap/viewer.html) and own study

2.2. Total heavy metal determination

Determination of the total concentrations of heavy metals (Cd, Cr, Cu, Ni, Pb, and Zn) in the sediment samples includes the following steps:

1) Sample preparation: 5 ml of nitric acid (HNO_3), 15 ml of hydrochloric acid (HCl), and 1 ml of hydrofluoric acid (HF) were added to 0.2 g of ground and sieved (0.2 mm) sediment sample.
2) Microwave digestion: the acid mixture and sediment sample were subjected to microwave digestion using the Multiwave 3000 system (Anton Paar GmbH, Austria).
3) Filtration: after the digestion process, the solution was filtered through paper filters to remove any solid residues or impurities, and diluted with 5% nitric acid (HNO_3) to a final volume of 50 ml.
4) Laboratory analysis: the analysis was performed using the Avio 200 ICP-OES atomic absorption spectrometer (PerkinElmer Inc., USA).
5) Results: the concentrations of heavy metals in the sediments were expressed in milligrams per kilogramme of dry matter ($mg \cdot kg^{-1}$).

2.3. Potential ecological risk assessment

Ecological risk assessment of heavy metals is essential to evaluate the potential adverse effects these pollutants may pose to the environment and ecosystems. In this study, the following criteria and indices were applied: geochemical quality classification (GQC) (Bojakowska, Sokołowska, 1998; Siebielec, Siebielec, Smreczak, 2015), Geoaccumulation Index (I_{geo}) (Müller, 1969), Ecotoxicological criteria (Macdonald, Ingersoll, Berger, 2000) and the Potential Ecological Risk Factor (ER) (Hakanson, 1980) (Table 1).

Table 1. The criteria and indices of potential ecological risk assessment of heavy metals

Criteria/Index	Equation	Category	Description
Geochemical quality classification	-	I	Non-contaminated (NC)
		II	Moderately contaminated (MC)
		III	Contaminated (C)
		IV	Highly contaminated (HC)

Criteria/Index	Equation	Category	Description
Geoaccumulation Index (I_{geo})	$I_{geo} = log_2\left(\frac{C_n}{1.5B_n}\right)$ C_n – measured concentration of an element in the sediment sample; B_n – geochemical background value	$I_{geo} \leq 0$ $0 < I_{geo} \leq 1$ $1 < I_{geo} \leq 2$ $2 < I_{geo} \leq 3$ $3 < I_{geo} \leq 4$ $4 < I_{geo} \leq 5$ $5 < I_{geo}$	Practically uncontaminated (PUC) Uncontam. to moderately contaminated (U-MC) Moderately contaminated (MC) Moderately to Heavily contaminated (M-HC) Heavily contaminated (HC) Heavily to Extremely contaminated (H-EC) Extremely contaminated (EC)
Ecotoxicological criteria	-	Metal < TEC[1)] PEC[2)] > Metal <TEC Metal > PEC	Non-toxic (NT) Neither non-toxic nor Toxic (0) Toxic (T)
Potential Ecological Risk Factor (ER)	$ER = T \cdot CF$ T – toxic response factor of the element; CF – Contamination Factor	ER < 40 40 < ER ≤ 80 80 < ER ≤ 160 160 < ER ≤ 320 ER > 320	Low risk (LR) Moderate risk (MR) Considerable risk (CR) High risk (HR) Very high risk (VHR)

[1)] TEC – Threshold Effect Concentration; [2)] PEC – Probable Effect Concentration

Source: based on literature data (Bojakowska, Sokołowska, 1998; Siebielec, Siebielec, Smreczak, 2015; Müller, 1969; Kabata – Pendias, 2011; Macdonald, Ingersoll, Berger, 2000; Hakanson, 1980)

2.4. Human health risks assessment

Assessment of the risks to human health caused by heavy metals in bottom sediments involves evaluating the potential adverse effects on human health resulting from exposure to these elements. Bottom sediments can accumulate heavy metals over time, and they can pose a risk, both to the health of adults and children. In this study, we decided to present two main routes through which heavy metals can enter the human body. The first one is accidental ingestion, while the second one is dermal contact (Jiménez-Oyola et al., 2021). The assessment of human health risks was performed using the methodology proposed by the United States Environmental Protection Agency (USEPA, 1989; 2001). The methodology is shown in Table 2.

Table 2. Methodology of human health risks assessment

Calculation of Average Daily Dose for heavy metals via ingestion and dermal contact ($mg{\cdot}kg^{-1}{\cdot}day^{-1}$)	
Average daily dose for incidental ingestion (ADD_{ing})	$ADD_{ing} = \frac{C \times IR_{ing} \times EF \times ED}{BW \times AT} \times CF$
Average daily dose for dermal contact (ADD_{derm})	$ADD_{dermal} = \frac{C \times SA \times AF \times ABS \times EF \times ED}{BW \times AT} \times CF$
C – heavy metal concentration in the sediment sample ($mg{\cdot}kg^{-1}$); IR_{ing} – ingestion rate ($mg{\cdot}day^{-1}$) (USEPA, 2002); EF – exposure frequency (day $year^{-1}$) (USEPA, 2002); ED – exposure duration (years) (USEPA, 2002); CF – conversion factor ($kg{\cdot}mg^{-1}$) (USEPA, 1989); BW – body weight (kg) (USEPA, 1989); AT – averaging time (days) (USEPA, 1989); SA – surface area (cm^2); AF – adherence factor ($mg{\cdot}cm^{-2}$) (USEPA, 2002); ABS – dermal absorption factor (USEPA, 2002)	
Non-carcinogenic risk assessment	
Hazard Quotient (HQ) (USEPA,1989; 2001)	$HQ_{ij} = \frac{ADD_{ij}}{RfD_{ij}}$
Hazard Index (HI) (USEPA, 1989; 2001)	$HI = \sum HQ_{ij}$
RfD – the reference dose of individual metal ($mg{\cdot}kg^{-1}{\cdot}day^{-1}$) (IRIS; Aendo et al., 2022) If the HQ or HI value > 1 – non-carcinogenic risk is possible; if the HQ or HI value < 1 – non-carcinogenic risk is not possible (USEPA, 1989; 2001)	
Carcinogenic risk assessment	
Carcinogenic Risk (CR) (USEPA, 1989; 2001)	$CR_{ij} = ADD_{ij} \times SF$
Total Carcinogenic Risk (TCR) (USEPA, 1989; 2001)	$TCR = \sum CR_{ij}$
SF – the cancer slope factor ($kg{\cdot}day{\cdot}mg^{-1}$) (Aendo et al., 2022; Miletić, Lučić, Onjia, 2023) If the CR or TCR values > $1{\times}10^{-4}$ – the carcinogenic risk occurs; if the values are between $1{\times}10^{-6}$ and $1{\times}10^{-4}$ – the carcinogenic risk is acceptable; if the values are < $1{\times}10^{-6}$ – the risk is not carcinogenic (USEPA, 1989; 2001).	

Source: based on the literature data (USEPA, 1989; USEPA, 2001; USEPA 2002; IRIS; Aendo et al., 2022; Miletić, Lučić, Onjia, 2023)

2.5. Statistical analysis

All calculations were performed using Statistica ver. 12.0 (StatSoft) and MS Excel (Microsoft). Pearson's correlation coefficients (r) were calculated to determine the relationships among different heavy metals in the bottom sediments. The statistical analyses were performed at a 95% confidence interval ($p < 0.05$).

3. Results and discussion

3.1. Heavy metals concentrations and distribution

The concentrations of heavy metals in the bottom sediments of the Pławniowice water reservoir are shown in Table 3. The highest concentrations of all elements were recorded at sampling point S3 (478.3 mg·kg^{-1}), while the lowest ones at S5 (322.6 mg·kg^{-1}). Considering the mean concentrations of heavy metals, they can be ordered in the decreasing series as follows: Zn>Pb>Cr>Cu>Ni>Cd. The series suggests that Zn was found to have the highest mean concentration among the studied metals, while concentration of Cd is the lowest. A similar tendency was observed in the sediments of the Kozłowa Góra (Tytła, Kernert, 2021) and Dzierżno Małe (Jaguś, Rzętała, Rzętała, 2013) reservoirs, which are also artificial water bodies, and are both located in the Silesian Voivodeship (Poland).

Table 3. Concentrations of heavy metals in the bottom sediments of the Pławniowice reservoir

Sampling point	Cd	Cr	Cu	Ni	Pb	Zn
	mg·kg^{-1}					
S1	3.4	32.8	27.7	19.6	40.9	223.6
S2	5.0	42.9	30.7	23.7	60.8	298.0
S3	4.2	44.6	32.1	21.2	54.0	322.2
S4	3.7	33.4	29.1	18.2	43.6	290.2
S5	3.7	32.4	22.6	13.9	29.9	220.0
$\overline{x}$	4.0	37.2	28.5	19.3	45.8	270.8
SD	0.6	6.0	3.6	3.6	12.0	46.3

$\overline{x}$ – mean; SD – standard deviation

Taking into account all sampling points, no unequivocal relationship has been ascertained between the concentrations of individual heavy metals and the depth of the reservoir, which indicates a minor impact of the reservoir morphometry on the allocation of the studied pollutants. The decreasing tendency was observed only between sampling points S3 (12 m) and S5 (15 m), which can be seen in Figure 2.

The Pławniowice reservoir is one of several man-made reservoirs in the Silesia Voivodeship. The obtained results indicate that sediments of the studied reservoir are characterized by lower levels of selected element concentrations as compared to other artificial water bodies in this region (Table 4). It should be mentioned that since 2003, the Pławniowice reservoir has been subjected to continuous reclamation using the so-called "Olszewski pipe", which is a specific type of hydrotechnical installation designed to reduce the ecosystem's abundance of biogenic substances

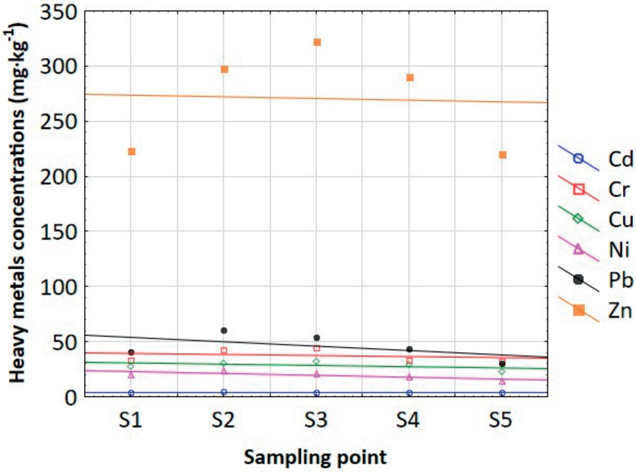

Figure 2. Heavy metals concentrations versus reservoir depth

(Kostecki, 2012). The reclamation process may also have, indirectly, a positive effect on the metal content. Table 4 presents the concentrations of heavy metals in various examples of artificial water reservoirs located in the study area.

Table 4. The concentrations of heavy metals in the bottom sediments of selected artificial water reservoirs located in the Silesian Voivodeship (Poland)

Reservoir	Cd	Cr	Cu	Ni	Pb	Zn	References
	mg·kg^{-1}						
Pławniowice	4.0	37.2	28.5	19.3	45.8	270.8	This study
Dzierżno Duże	8.4	111.1	143.3	49.4	165.6	1353.6	(Tytła, Kostecki, 2019)
Dzierżno Małe	2.4	66.1	21.5	23.8	69.6	342.6	(Jaguś, Rzętała, Rzętała, 2013)
Rybnik	6.9	89.4	1329.0	59.4	64.8	1287.0	(Pohl et al., 2022)
Kozłowa Góra	17.5	51.6	43.6	22.0	388.2	2306.0	(Tytła, Kernert, 2021)

Source: based on literature data (Tytła, Kostecki, 2019; Jaguś, Rzętała, Rzętała, 2013; Pohl et al., 2022; Tytła, Kernert, 2021) and own study

Because the concentrations of heavy metals in sediments at individual sampling points were characterized by low variability, we averaged their values. This approach simplifies data analysis and reduces the impact of random fluctuations or outliers that might exist at specific sampling points. Therefore, for further analyses, the mean values of heavy metals concentrations were used.

Pearson's correlation coefficient (*r*) is specifically used to quantify the strength and direction of the linear relationship between two variables, in this study, the analysed heavy metals. The conducted analyses confirmed that between Cr and Pb; Cu and Ni; Cu and Pb; Cu and Zn, and also Ni and Pb, significant positive correlations exist ($r>0.88$). However, strong, but not statistically significant correlations have also been observed between Cd and Cr; Cd and Pb; Cr and Zn, and Pb and Zn ($r>0.82$). The strong correlations between various heavy metals in sediments of various water bodies have also been reported in other scientific papers (Pohl et al., 2022; Şimşek, Özkoç, Bakan, 2022). The results of the statistical analysis are shown in Table 5.

Table 5. Pearson correlation matrix of heavy metals in the bottom sediments

	Cd	Cr	Cu	Ni	Pb	Zn
Cd	1.0000					
Cr	0.8279	1.0000				
Cu	0.5454	0.7837	1.0000			
Ni	0.7121	0.7761	***0.8814**	1.0000		
Pb	0.8313	***0.8793**	***0.9044**	***0.9616**	1.0000	
Zn	0.6566	0.8217	***0.8803**	0.6722	0.8233	1.0000

*$p<0.05$

The existence of strong correlations between different heavy metals suggests a common source of pollution. This is because industrial and human activities, as well as natural processes, may release multiple elements into the natural environment simultaneously, leading to their co-occurrence in different ecosystems (Şimşek, Özkoç, Bakan, 2022). However, taking into account previous reports on the presence of heavy metals in the bottom sediments of the Pławniowice reservoir, the most probable way through which this pollutant gets into sediments is dry and wet deposition from the atmosphere and surface runoff from the direct catchment area (Machowski, Rzętała, 2020). Considering the poor air quality in the Silesian Voivodeship and the proximity of the DK40 road and the A4 motorway, it can be assumed that these factors are one of the probable sources of these elements in sediments of the studied reservoir.

3.2. Results of potential ecological risk assessment

The potential ecological risk assessment of heavy metals is strongly associated with the evaluation of the hazardous properties of these elements and their negative influence on various ecosystems and living organisms (mainly aquatic organisms). The results of the potential ecological risk assessment are presented in Table 6.

Table 6. Ecological risk of heavy metals in the bottom sediments

Heavy metal	Geochemical quality classification (GQC)	Geoaccumulation Index (I_{geo})	Ecotoxicological criteria	Potential Ecological Risk Factor (ER)
Cd	III	4.7 (H-EC)	0	1207.1 (VHR)
Cr	I	–2.0 (PUC)	NT	0.7 (LR)
Cu	I	–1.5 (PUC)	NT	2.6 (LR)
Ni	II	–0.6 (PUC)	NT	4.8 (LR)
Pb	II	1.0 (U-MC)	0	15.3 (LR)
Zn	II	1.4 (MC)	0	3.9 (LR)

According to the geochemical quality classification (Bojakowska, Sokołowska, 1998; Siebielec, Siebielec, Smreczak, 2015), the bottom sediments of the Pławniowice reservoir are mainly contaminated with Cd (class III), moderately contaminated with Ni, Pb, and Zn (class II), and non-contaminated by Cr and Cu (class I). In this respect, the Pławniowice water reservoir stands out from other water bodies in the Silesian Voivodeship, which is an area characterized by a high concentration of heavy metals in the environment. However, the concentrations of metals in the analysed bottom sediments are still higher than in sediments from reservoirs located in other parts of the country, such as in the Greater Poland Voivodeship (Sojka, Jaskuła, Siepak, 2019) or the Warmian-Masurian Voivodeship (Świercz, Tomczyk-Wydrych, Bąk, 2022).

The Geoaccumulation Index (I_{geo}) (Müller, 1969) assesses the degree of sediment contamination and classifies metal levels into different classes, indicating the degree of ecological risk. The values of I_{geo} indicated that the sediments under study were heavily to extremely contaminated by Cd and moderately contaminated by Zn. This suggests that cadmium may pose a potential risk to the studied ecosystem. A similar tendency was observed in the previous study (Tytła, Kostecki, 2019), where the sediments of the Dzierżno Duże reservoir (Silesian Voivodeship, Poland) were analysed (I_{geo} – Cd; 4.7 – 5.9).

Based on the ecotoxicological criterion, which involves evaluating the Probable Effect Concentration (PEC) and the Threshold Effect Concentration (TEC) (Macdonald, Ingersoll, Berger, 2000), the study revealed that the metals present in the bottom sediments of the Pławniowice reservoir generally do not exhibit a toxic effect on benthic organisms. However, in the case of Cd, Pb, and Zn, the concentrations of these metals exceeded TEC values, which means that they are neither non-toxic nor toxic for aquatic organisms. Similar research was conducted by other scientists who analysed the same metals as we did, but in the sediments of the Sołtmany Lake (Masurian Lake District, Poland) (Świercz, Tomczyk-Wydrych, Bąk, 2022). They indicated that the TEC value was exceeded only for Cd, while the PEC values have not been exceeded in any of the cases. Therefore, the presented study confirms that sediments from the water bodies located in the Silesian Voivodeship are still more contaminated by heavy metals than those from other parts of the country.

The Potential Ecological Risk Factor (ER) (Hakanson, 1980) is applied to the ecological risk assessments of heavy metals in various environmental samples. The ER index includes both the concentration of the heavy metals and their toxicities. The conducted calculations revealed that from among the studied heavy metals only cadmium may pose a serious ecological risk. Moreover, high ER values for Cd are most probably associated with the high value of the toxic response factor for this element, which equals to 30. However, it is commonly observed that metals that occur in low concentrations in the environment are very often the most toxic ones. For comparison, another team of scientists analysed the concentrations of selected heavy metals in bottom sediments collected from the 28 water reservoirs in Poland and have found that ER values for studied elements formed the following series: Cd>Cu>Ni>Pb>Cr>Zn (Sojka et al., 2023). The above-mentioned results are in good agreement with those presented in our study.

3.3. Results of human health risks assessment

3.3.1. Exposure assessments

ADD refers to the amount of heavy metal that individuals might be exposed to daily through various pathways, such as accidental ingestion (ADD_{ing}) or direct contact with sediments (ADD_{derm}). The values of the average daily exposure doses (ADDs) are shown in Table 7.

The obtained results have revealed that the main pathway of heavy metals exposure was accidental ingestion. Moreover, higher values of ADDs were found for children. This means that they are more vulnerable to the health risks associated with exposure to analysed elements. Similar observations were also made by other scientists (Jiménez-Oyola et al., 2021; Sojka et al., 2023). The highest values of ADD_{ing} were obtained for Zn, i.e., 3.71×10^{-4} mg·kg^{-1}·day^{-1} and 3.25×10^{-3} mg·kg^{-1}·day^{-1} for adults and children, respectively, while in the case of ADD_{derm} 1.48×10^{-6} and 9.09×10^{-6} mg·kg^{-1}·day^{-1}. The lowest ADD_{ing} and ADD_{derm} for adults and children were indicated for Cd, i.e., 2.36×10^{-6}mg·kg^{-1}·day^{-1} and 9.42×10^{-9}mg·kg^{-1}·day^{-1}, as well as 4.13×10^{-6}mg·kg^{-1}·day^{-1} and 1.16×10^{-8} mg·kg^{-1}·day^{-1}, respectively.

Table 7. Average daily exposure doses of heavy metals in bottom sediments

Heavy metal	Adults			Children		
	ADD_{ing}	**ADD_{derm}**	**ADD**	**ADD_{ing}**	**ADD_{derm}**	**ADD**
Cd	2.36×10^{-6}	9.42×10^{-9}	2.37×10^{-6}	4.13×10^{-6}	1.16×10^{-8}	4.14×10^{-6}
Cr	2.18×10^{-5}	8.71×10^{-8}	2.19×10^{-5}	3.82×10^{-5}	1.07×10^{-7}	3.83×10^{-5}
Cu	3.90×10^{-5}	1.56×10^{-7}	3.91×10^{-5}	3.41×10^{-4}	9.55×10^{-7}	3.42×10^{-5}
Ni	1.13×10^{-5}	4.52×10^{-8}	1.14×10^{-5}	1.98×10^{-5}	5.55×10^{-8}	1.99×10^{-5}
Pb	2.69×10^{-5}	1.07×10^{-7}	2.70×10^{-5}	4.71×10^{-5}	1.32×10^{-7}	4.72×10^{-5}
Zn	3.71×10^{-4}	1.48×10^{-6}	3.72×10^{-4}	3.25×10^{-3}	9.09×10^{-6}	3.25×10^{-3}

3.3.2. Non-carcinogenic and carcinogenic risks assessment

According to the International Agency for Research on Cancer (IARC) (2012), metals such as cadmium, chromium, nickel and lead are classified as carcinogenic, which means that they can pose significant risks to public health even at low levels of exposure. Moreover, long-term exposure to these toxic elements can lead to various health issues, such as: organ damage, neurological disorders, as well as an increased risk of cancer (Şimşek, Özkoç, Bakan, 2022). For this purpose, in this study the carcinogenic risk was assessed only in the case of Cd, Cr, Ni, and Pb, whereas for Cu and Zn, the evaluation of the non-carcinogenic risk was conducted. The results of the human health risks assessment are presented in Table 8.

Table 8. Human health risks from heavy metals in the bottom sediments

Non-carcinogenic risk						
Heavy metal	**Adults**			**Children**		
	HQ_{ing}	HQ_{derm}	HI	HQ_{ing}	HQ_{derm}	HI
Cu	9.74×10^{-4}	1.30×10^{-5}	9.87×10^{-4}	8.53×10^{-3}	7.96×10^{-5}	8.60×10^{-3}
Zn	1.24×10^{-3}	2.47×10^{-5}	1.26×10^{-3}	1.08×10^{-2}	1.51×10^{-4}	1.10×10^{-2}
Carcinogenic risk						
Heavy metal	**Adults**			**Children**		
	CR_{ing}	CR_{derm}	TCR	CR_{ing}	CR_{derm}	TCR
Cd	1.49×10^{-5}	5.74×10^{-8}	1.49×10^{-5}	2.60×10^{-5}	7.05×10^{-8}	2.61×10^{-5}
Cr	1.09×10^{-5}	1.74×10^{-6}	1.27×10^{-5}	1.91×10^{-5}	2.14×10^{-6}	2.12×10^{-5}
Ni	1.93×10^{-5}	1.92×10^{-6}	2.12×10^{-5}	3.37×10^{-5}	2.36×10^{-6}	3.61×10^{-5}
Pb	2.29×10^{-7}	nd	2.29×10^{-7}	4.00×10^{-7}	nd	4.00×10^{-7}

nd – no data on SF value for Pb by dermal contact

Non-carcinogenic risk assessment

Based on the obtained results and the values of the Risk Quotient (HQ) and the Hazard Index (HI) for non-carcinogenic heavy metals, i.e., Cu and Zn, the accidental ingestion of polluted sediments was identified as the primary exposure pathway for both demographic groups (adults and children), with a particular emphasis on children. The conducted calculations revealed that the HQ and HI values for Cu and Zn did not exceed the threshold value of 1 (USEPA, 1989; 2001), which suggests that the potential health risks associated with exposure to these metals through the specific pathways were below levels of concern for non-carcinogenic effects. Therefore, in this case, there is no non-carcinogenic risk posed to humans or other organisms living in the analysed water body, either by ingestion or dermal contact with sediments from the Pławniowice reservoir. Similar research was conducted by other researchers who analysed sediments from Ecuador, and documented that the values of HQ and HI related to Cu and Zn exposure in both demographic groups were extremely low (Jiménez-Oyola et al., 2021).

Carcinogenic risk assessment

The conducted study indicated that the values of Carcinogenic Risk (CR) and Total Carcinogenic Risk (TCR) for toxic metals (Cd, Cr, Ni, and Pb) in the analysed sediments were below 1×10^{-4} (USEPA, 1989; 2001) for both demographic groups, which means that the direct carcinogenic risk did not occur. As in the case of non-carcinogenic metals, the main exposure pathway was accidental ingestion, and higher values of CR and TCR were calculated for children. However, in the case of Cd, Cr, and Ni (CR_{ing}), and Cr and Ni (CR_{derm}) for both for adults and children, the values for CRs were in the range 10^{-6} – 10^{-4} (USEPA, 1989; 2001). Also, the values of TCRs confirmed the above findings, which suggests that the carcinogenic risk is acceptable. In this case, appropriate steps must be taken to reduce the possible impact of Cd, Cr and Ni on human health. One of the solutions that could be implemented is the periodical removal of sediments from the reservoir. The study related to the carcinogenic risk assessments was also conducted by scientists from Nigeria who analysed As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn in the sediments and indicated that for the above-mentioned elements, the carcinogenic risk was non-existent (Wuana et al., 2020).

4. Conclusions

The bottom sediments of the Pławniowice reservoir are practically non-contaminated to moderately contaminated by analysed heavy metals, except cadmium. This is a unique phenomenon because the Silesian Voivodeship is a region where the concentrations of these pollutants in the environment are very high. This may indicate a small impact of anthropopressure in the basin of this reservoir compared to other water bodies in the study area.

In the course of the research, no unequivocal relationship have been ascertained between the concentrations of individual heavy metals and the depth of the reservoir, which indicates a minor impact of the reservoir morphometry on the allocation of the tested pollutants. In turn, the statistical analysis showed a strong correlation between the individual metals in the analysed bottom sediments, which may point to their common source of origin. According to the classification based on the geochemical quality classification, the bottom sediments of the Pławniowice reservoir are contaminated with Cd (Class III) and moderately contaminated with Ni, Pb, and Zn (Class II).

The results of the ecological risk analysis based on the I_{geo} and ER indices indicate that the potential threat to the fauna and flora of the Pławniowice reservoir may only be caused by the presence of cadmium. In turn, the ecotoxicological criteria revealed that none of the analysed elements are toxic to the benthic organisms in the studied reservoir.

The human health risks assessment indicates that the primary exposure pathway for both demographic groups may be accidental ingestion of polluted sediments. In both cases, children are more exposed to the health effects. The obtained results suggest that there were no non-carcinogenic risks of Cu and Zn. Moreover, it was found that the carcinogenic metals do not pose a direct threat to human health, but the values of the CRs and TCRs for Cd, Cr, and Ni were in the range of 10^{-6} – 10^{-4}, which points to a relatively low to moderate level of risk. Therefore, in this case, it is recommended to take appropriate steps to reduce the concentrations of these metals in the sediments by their removal. The frequency and schedule of sediment removal should be established based on the analysis and monitoring of the selected heavy metal concentrations in the studied bottom sediments.

The obtained results indicate that the assessment of the real threat associated with the accumulation of heavy metals in bottom sediments required a comprehensive risk analysis. Moreover, understanding the sources of heavy metals in bottom sediments is still crucial for effective environmental management. Therefore, further research should be addressed at identifying of the sources of heavy metal contamination, which can help authorities implement targeted mitigation strategies, prevent secondary pollution, and ensure the safety of aquatic ecosystems and human populations.

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ANALIZA RYZYKA EKOLOGICZNEGO I ZDROWOTNEGO ZWIĄZANEGO Z OBECNOŚCIĄ METALI CIĘŻKICH W OSADACH DENNYCH ZBIORNIKA WODNEGO PŁAWNIOWICE – SZTUCZNE JEZIORO (WOJEWÓDZTWO ŚLĄSKIE, POLSKA)

Abstrakt

Celem pracy jest ocena ryzyka ekologicznego i zdrowotnego związanego z obecnością metali ciężkich (Cd, Cr, Cu, Ni, Pb i Zn) w osadach dennych zbiornika Pławniowice, który znajduje się w województwie śląskim, jednym z najbardziej zanieczyszczonych regionów w kraju. Próbki do badań pobierano w pięciu punktach rozmieszczonych wzdłuż głównej osi zbiornika. Stężenia metali ciężkich oznaczano przy użyciu spektrometru absorpcji atomowej Avio 200 ICP-OES (PerkinElmer Inc.). Do oceny ryzyka ekologicznego wykorzystano geochemiczne klasy czystości osadów, Geoaccumulation Index (I_{geo}), Ecotoxicological criteria oraz Potential Ecological Risk Factor (ER), z kolei do oceny ryzyka zdrowotnego użyto Hazard Quotient (HQ), Hazard Index (HI), Cancirogenic Risk (CR) oraz Total Carcinogenic Risk (TCR). Wyniki analizy ryzyka ekologicznego wskazują, że spośród badanych metali tylko Cd może stanowić potencjalne zagrożenie dla fauny i flory zbiornika. Ocena ryzyka zdrowotnego wykazała, że główną drogą narażenia dla dorosłych i dzieci może być przypadkowe połknięcie zanieczyszczonych osadów. Ponadto w obu przypadkach dzieci są bardziej narażone na skutki zdrowotne. Pomimo że analizowane metale nie stwarzały bezpośredniego zagrożenia dla zdrowia człowieka, to ze względu na wartości indeksów CR i TCR, w odniesieniu do Cd, Cr i Ni, zaleca się podjęcie odpowiednich działań w celu zmniejszenia stężeń tych metali ciężkich w osadach dennych poprzez ich okresowe usuwanie.

Słowa kluczowe: osady denne, metale ciężkie, ryzyko ekologiczne, ryzyko zdrowotne, sztuczny zbiornik wodny