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# Integrated assessment of heavy metal contamination and ecological risk in bottom sediments of the Dobromierz drinking water reservoir, Poland

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**Abstract:** The aim of this study was to assess the degree of heavy metal contamination (cadmium - Cd, chromium - Cr, copper - Cu, nickel - Ni, lead - Pb, zinc - Zn) and the potential ecological risk of bottom sediments in the Dobromierz drinking water reservoir (Poland). The study involved sampling within the reservoir's direct and indirect protection zones and at reference points on the Strzegomka River over two seasons (autumn 2023 and spring 2024). Laboratory analyses were performed using the ICP-OES method after sample mineralization in aqua regia, and integrated indicators were used to assess toxicity: the geochemical approach, the Länder-Arbeitsgemeinschaft Wasser Classification (LAWA), the pollution index (Pi), the geoaccumulation index (Igeo), the contamination factor (Cf) and the ecological risk index (Er).

The results indicate that the dominant sediment fraction in the reservoir consists of earthy particles (<2 mm), which favor the accumulation of heavy metals. The highest median metal concentrations were recorded in the direct protection zone, as confirmed by the toxicity indicator values. The order of metal toxicity was as follows: Cd > Cu > Ni > Cr > Zn > Pb. The sediments were mostly classified as Class I-II toxicity (slightly or moderately contaminated), but remediation was required at several locations due to elevated Cu and Ni levels. Cluster analysis confirmed the similarity of sediment properties in the reservoir's protection zones and their distinction from samples collected from the Strzegomka River.

The results emphasize the importance of comprehensive, multi-indicator assessment methods in diagnosing the ecotoxicity of bottom sediments in drinking water reservoirs. This study fills a knowledge gap regarding heavy metal pollution in Poland and provides a basis for implementing remedial measures and sustainable water resource management.

## Introduction

Heavy metal accumulation in bottom sediments poses a critical threat to the ecological safety of drinking water reservoirs, profoundly impacting both water quality and the health of aquatic ecosystems. The reservoir sediment system functions as a complex matrix that integrates organic matter, diverse metallic elements, microbial communities, and inorganic substances (Zhu, 2013; Lee et al., 2021). Within this intricate environment, sediments act simultaneously as both a source and a sink for pollutants, playing a central role in the transport

and sequestration of potentially hazardous heavy metals (Liu, 2023; Zhu, 2013). These metals are typically adsorbed from the water column onto the surfaces of fine particles before being deposited into the benthos. Research indicates that over 99% of heavy metals entering aquatic ecosystems are eventually stored within these sediments (Liu, 2023; Gwimbi et al., 2020). However, sediments also represent a significant internal source of pollution, as heavy metals can be remobilized and released back into the overlying water column in response to natural environmental fluctuations or anthropogenic activities.

The ecotoxicity of sediment-bound metals is largely governed by their mobility and bioavailability, factors that directly influence ecological stability and human health (Zhu, 2013). While the toxicological effects of specific metals vary, their concentrations serve as reliable indicators of overall ecosystem integrity. Consequently, evaluating the potential ecological risk associated with heavy metal contamination has become a standard diagnostic approach in water pollution management (Wang et al., 2012). Numerous indicators have been developed to quantify contamination levels and the resulting ecological risks (Debnath et al., 2021). Classical assessment indices include the geochemical approach index (Pierwoła et al., 2020), the Länder-Arbeitsgemeinschaft Wasser Classification (LAWA) (Nawrot et al., 2021), the pollution index (Pi) (Ferreira et al., 2022), the geoaccumulation index (Igeo) (Tomczyk et al., 2022), the contamination factor (Cf) (Vu et al., 2017), and the ecological risk index (Er) (Benson et al., 2018). Because reliance on a single indicator can result in biased assessments and potentially erroneous management decisions (Li, 2025), the integration of multiple indices is widely regarded as the preferred methodology for comprehensive and reliable sediment pollution assessment (Yang et al., 2023). Accordingly, this study employs a multi-indicator framework to capture both spatial variability and ecological risk gradients in drinking water reservoirs.

A multi-indicator assessment framework using, among others, the geoaccumulation index (Igeo), the pollution index (Pi), and the ecological risk index (Er) was applied by Zhou et al. (2020) to evaluate heavy metal enrichment in the sediments of the Shuanglong drinking water reservoir in China. Their findings indicated that sediments contamination originated primarily from industrial activities rather than natural processes. As demonstrated in numerous studies (Zhu et al., 2013, Wang et al., 2015, Chen et al., 2019, Zhou et al., 2023, Li et al., 2025), Chinese drinking water reservoirs have been extensively investigated using pollution assessment indices. Based on Ef and Igeo values, Zhu et al. (2013) reported contamination levels following the order  $Zn > Cr > Ni > Cu > Pb > Cd$ , with mean concentrations generally below average shale values.

Similarly, Cüce et al. (2022) conducted a multi-indicator analysis of bottom sediments in the Ömerli drinking water reservoir in Turkey. Their results revealed significant contamination by cadmium (Cd), mercury (Hg), and lead (Pb), attributed mainly to anthropogenic sources. Average metal concentrations followed the order (mg/kg):  $Zn (180.81) > Cr (117.26) > Pb (94.76) > Ni (63.67) > Cu (53.11) > Cd (1.76)$ .

Multi-indicator sediment analyses have been conducted in Polish water reservoirs (Sojka et al., 2019, Kulbat and Sokołowska, 2019). Sojka et al., (2019) emphasized that heavy metal concentrations in bottom sediments represent reservoir-specific characteristics. Their assessment indicated that metals such as cadmium (Cd), chrome (Cr), copper (Cu), nickel (Ni), and lead (Pb) in western Polish reservoirs primarily originate from geogenic sources associated with rock weathering. Mean concentrations followed the order of  $Zn > Pb > Cu > Cr > Ni > Cd$ , with Zn reaching an average of 452.2 mg/kg. Kulbat and Sokołowska (2019), using the geochemical approach index and Igeo, demonstrated significant Cr contamination, with average concentrations of Cu, Ni, and Cr exceeding background levels by factors of 3.4, 3.9, and 21.2 respectively. Collectively, these

studies confirm that robust and widely accepted methodologies for sediment contamination assessment already exist, and further application, including in the present study, enhances the accuracy and comparability of environmental evaluations.

As a critical source of drinking water for over 21,000 residents in southwestern Poland, the Dobromierz Reservoir plays a vital role in regional public health and water security (Szewczyk et al., 2024). Despite its importance, the contamination profile of its bottom sediments remains insufficiently characterized, leaving a significant gap in understanding the reservoir's long-term ecological condition. This study addresses this deficiency by investigating spatiotemporal variations in the concentrations of copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni) in bottom sediments, with the objective of identifying potential ecological risks and supporting targeted remedial strategies.

In an era marked by declining water resources and increasing climate variability, the assessment of sediment quality in drinking water reservoirs represents an essential yet underexplored research domain in Poland. By establishing baseline data on sediment contamination, this study offers a critical perspective on regional environmental management. Furthermore, the proposed analytical framework, integrating sediment granulometric properties with multi-indicator toxicity assessment, addresses a persistent methodological gap in sediment ecotoxicology.

Ultimately, the findings of the study align with the broader objectives of sustainable development, particularly Sustainable Development Goal 6, "Clean Water and Sanitation," supporting policies aimed at rational water management and the protection of public health through the provision of safe and high-quality drinking water.

## Materials and Methods

### Study design

The research was conducted at selected research sites within the Dobromierz Reservoir (50°54'3"N, 16°14'45"E), located in southwestern Poland, within the Dobromierz commune. Its main function is to supply drinking water to the town of **Świebodzice**. Owing to its role as a drinking water source, the reservoir is subject to sanitary protection zones, including direct protection (encompassing the Dobromierz Reservoir and a shoreline buffer zone of 0.16 km<sup>2</sup>) and indirect protection (covering the Strzegomka River catchment area with its tributaries of 19.21 km<sup>2</sup>) (Szewczyk et al., 2025). The designated sanitary protection areas are subject to a system of prohibitions, regulations, and restrictions. In the direct protection zone, land use unrelated to the operation of the water intake is prohibited, and access is limited to authorized personnel. In the indirect protection zone, activities such as discharge of sewage into surface waters and soils, the siting of landfills and liquid waste disposal facilities, camping and water sports, the application of artificial fertilizers and plant protection products, vehicle washing, the establishment of cemeteries, and the burial of animals are prohibited. The boundaries of the protection zones are marked with information boards, and part of the direct protection area, including infrastructure, is fenced. Warning signs posted throughout the reservoir area indicate restricted access and a permanent bathing ban (Cietrzewska and Sroka-Nowicka, 2013).



**Fig. 1.** Map of research points on the Dobromierz reservoir in Poland (D – direct protection zone, I – indirect protection zone, R – reference points; background: [https://mapy.geoportal.gov.pl/imap/lmgp\\_2.html?gpmmap=gp0](https://mapy.geoportal.gov.pl/imap/lmgp_2.html?gpmmap=gp0))

For the purposes of the study, three zones were distinguished: the direct protection zone (D), the indirect protection zone (I) within the Dobromierz Reservoir, and a reference zone (R) on the Strzegomka River.

### Study area

Constructed between 1977 and 1986 on the mountainous Strzegomka River, the Dobromierz Reservoir covers an area of 103 hectares and has a total storage capacity of 10 million m<sup>3</sup>. Situated in the northern part of its catchment, the reservoir lies within a transitional geographical zone at the boundary between the Bolkowskie and Wałbrzych Foothills. Its ecological significance is underscored by its inclusion within protected areas, specifically the Natura 2000 site Dobromierz PLH020034 and the Książański Landscape Park (Wawrzyniak, 2022). The surrounding catchment forms part of the Central Sudetes macroregion, where elevations typically range from 400 to 500 meters above sea level. An average catchment slope of 5.2% promotes substantial surface runoff, thereby intensifying soil erosion processes from the surrounding agricultural land (Lejcuś, 2004; Dąbrowska et al., 2018).

The climate of the Strzegomka River basin is stratified into two altitudinal zones. Zone I, located below 550 meters, experiences an average annual temperature between 6.1 and 6.6°C, with mean growing-season temperatures reaching approximately 12°C over a period of about 200 days. In contrast, Zone II, encompassing areas above 550 meters, is characterized by cooler conditions, with annual mean temperatures ranging

from 5.0 to 5.5°C and an average growing-season temperature of 11°C lasting approximately 185 days. Precipitation across the basin is unevenly distributed, increasing with elevation to an average annual total of 680 mm (Lejcuś, 2004).

Semi-permeable soils dominate the catchment, which is primarily characterized by intensive agricultural use. Land use comprises approximately 60% agricultural land, including meadows and pastures, 32% forest cover consisting mainly of mixed and coniferous stands, and 8% built-up areas (Dąbrowska et al., 2018). These soils have developed from weathered sedimentary, igneous, and metamorphic rocks, forming predominantly brown and podzolized soils with a medium- to heavy-textured silty clay composition. Chemically, they are characterized by high humus content, elevated hydrolytic acidity, substantial potassium availability, and low phosphorus levels. Soil pH is strongly acidic (<4.5), base cation saturation is below 20%, and a carbon-to-nitrogen (C/N) ratio is approximately 20 (Lejcuś, 2004).

Environmental pressures within the reservoir's catchment are dominated by diffuse pollution sources, including municipal wastewater and fertilizer runoff from agricultural fields. Although over 70% of residents in the Dobromierz commune are connected to the municipal sewer network, with wastewater treated at the Serwinów and Czernica treatment plants, sanitation infrastructure in rural areas remains inadequate. In these areas, wastewater is predominantly managed using septic tanks and small domestic treatment systems, which continue to pose a potential risk to surface water quality (Szewczyk et al., 2025).

### Sampling procedure

Sampling was carried out in two existing zones: direct (D; samples D1-D7) and indirect (I; samples I1-I10). Additionally, two reference points were designated upstream and downstream of the reservoir on the Strzegomka River (samples R1 and R2). In total, 19 research points were identified, from which samples were collected in two measurement series in autumn 2023 and spring 2024 (once at each research point). Bottom sediments were collected using an Ekman-Birge bottom sampler (box dimensions 15 x 15 x 20 cm, catch area 225 cm<sup>2</sup>); deployed on a rope. Field sampling on the reservoir was carried out from a boat. The locations of the research points are shown in Figure 1.

Spatial and temporal variability in sampling allowed assessment of changes in sediment properties. At each location, at least 1 liter of the top layer of hydrated sediment (approximately 3 cm thick), representing the active exchange layer recently deposited, was collected. Samples were placed in polyethylene bags, appropriately labeled, and then transported under refrigeration to the laboratory, where they were labeled.

During sediment sampling, water quality parameters were also analyzed using the YSI EXO2 multiparameter probe (Nowiński, 2024).

### Laboratory tests

Prior to analysis, sediment samples were stored under controlled conditions at approximately 20°C in a dry, dark environment to preserve their integrity. All analytical procedures were conducted in triplicate using thoroughly homogenized, air-dried samples at the Center for Environmental Quality Analysis, Wrocław University of Environmental and Life Sciences, an institution accredited (AB 1293) for heavy metal determination (Wdowczyk et al., 2024). Heavy metal concentrations were determined following microwave-assisted digestion in aqua regia, in accordance with the US EPA 3051A protocol, and subsequent analysis by inductively coupled plasma atomic emission spectrometry (ICP-OES) (Tomczyk et al., 2022). Measurement were performed using a Thermo Scientific iCAP 7400 ICP-OES spectrometer, calibrated according to the manufacturer's specifications with Merck standard solution (QC1132-20ML). Calibration standards were prepared in a matrix of 6% hydrochloric acid and 2% nitric acid, with element concentrations strategically selected to cover the necessary analytical range.

To ensure analytical accuracy, an internal standard solution of yttrium (5 mg/L) was introduced online through an internal standard mixing kit, with emission wavelengths matched to those of the target analytes. Rigorous quality control procedures included regular measurements of blanks and replicate samples at a frequency of at least one per twenty samples (Tomczyk et al., 2026). The analytical ranges ((dry weight basis) were 0.05-500 mg/kg for Cu and Pb, 2.0-1000 mg/kg for Zn, 0.005-500 mg/kg for Cd, 0.1-500 mg/kg for Cr, and 1.0-500 mg/kg for Ni. For concentrations below the limits of detection (LOD), values equal to half LOD were assigned. The specific limits of quantification (LOQ) were 0.15 mg/kg for Cu and Pb, 6.03 mg/kg for Zn, 0.015 mg/kg for Cd, 0.3 mg/kg for Cr, and 2.98 mg/kg for Ni (Wdowczyk et al., 2024).

The granulometric composition of sediments was determined using the Bouyoucos areometric method, modified

by Casagrande and Prószyński, with particle-size fractions separated by sieving (Tomczyk et al., 2022). Sediment texture was classified according to the United States Department of Agriculture (USDA) standards into clay (<0.002 mm), silt (0.002 to 0.05 mm), and sand (0.05 to 2.00 mm) fractions (Moreno-Maroto and Alonso-Azcárate, 2022). Additionally, sediment material was divided into skeletal (>2 mm) and earthy fractions.

### Statistical analysis

For the purposes of the study, basic descriptive statistics were calculated, including the minimum, mean, median, maximum, standard deviation, and coefficient of variation. These statistics are presented in tables and as box plots, stratified by sampling groups: R - reference points upstream and downstream the reservoir, D - direct zone of the reservoir, and I - indirect zone of the reservoir.

Additionally, hierarchical cluster analysis was performed using point-wise clustering (Ward's method, Euclidean distance) to identify potential similarities and differences among sampling locations. The analyses were conducted using two datasets: the first included heavy metal concentrations and mean grain diameter ( $D_{50}$ ) as input variables, while the second consisted of toxicity index values.

### Toxicity indices

In this study, the quality of seabed sediments was assessed using the following indices: geochemical approach (Pierwoła et al., 2020), LAWA classification (Nawrot et al., 2021), pollution index (Pi) (Ferreira et al., 2022), geoaccumulation index (Igeo) (Tomczyk et al., 2022), contamination factor (Cf) (Vu et al., 2017), and ecological risk index (Er) (Benson et al., 2018). These six indices were selected because they are based on different conceptual frameworks, including geochemical approach and standard metal values, contamination assessment, ecological risk analysis, while remaining directly comparable through a unified five-class toxicity classification. Four of the six indices additionally apply the same scoring scale (0 - 100). Consequently, the combined use of these indices provides a comprehensive assessment of sediment quality and potential toxicity, as described in previous studies (e.g., Sałata et al., 2023), provide information on the potential toxicity of sediments (in this case, heavy metals). For the geochemical and LAWA methods, classification was based on measured heavy metal concentrations and subsequently converted into a unified five-class scale, consistent with the remaining four indices (Table 1), which were calculated using Equations (1-4). The results were grouped according to the sampling location points: R - reference sites, D - direct zone, and I - indirect zone.

$$Pi = \frac{Ci}{Si} \quad (1)$$

where: Pi is Pollution Index; Ci is the concentration of i-th metal in the sample; Si is the secondary standard value of the i-th metal (according to Hakanson, 1980): Cu = 50 mg/kg, Ni = 30, Cr = 90, Zn = 175, Pb = 70, Cd = 1);

$$Igeo = \log 2 \left( \frac{Ci}{1.5Bi} \right) \quad (2)$$

where: Igeo is Geoaccumulation Index, and Bi is background level of metal i (in Poland according to the geochemical

classification: Cu = 6 mg/kg, Ni = 5, Cr = 5, Zn = 48, Pb = 10, Cd = 0.5; Tomczyk et al., 2022);

$$Cf = \frac{Ci}{Bi} (3)$$

where: Cf is the Contamination Factor.

$$Er = Tr \cdot Cf (4)$$

where: Er is the Ecological Risk Index, and Tr is the toxicity coefficient of each metal (Cu = 5 mg/kg, Ni = 5, Cr = 2, Zn = 1, Pb = 5, Cd = 30).

In the case of the geochemical and LAWA methods, the mean was used in the sediment analyses, whereas in the remaining cases the median was applied. This choice reflects the fact that the geochemical and LAWA methods assign measured concentrations to toxicity classes; consequently, the median would merely represent the midpoint of a given class and would not capture the variability of the results. In contrast, the mean allows such variability to be incorporated through weighted class values (i.e., class I - 1, II - 2, III - 3, IV - 4, V - 5). For the remaining methods, the median was preferred over the mean because it is less sensitive to outliers and therefore provides a more robust representation of the actual conditions. Moreover, the calculated index values in these methods are expressed on a continuous scale rather than as discrete classes, as in the two former approaches.

The following software packages were used for the analyses: SPSS Statistics 26, Origin Pro 2022b, Statistica 13, Microsoft Office LTSC 2021 (Excel, Word, PowerPoint), PhotoScape and QGIS 3.34.14.

## Results and Discussion

### Water quality

To provide broader context, the variability of selected water quality parameters was assessed using a YSI EXO2 multiparameter probe. This analysis incorporated data from the 19 previously described study sites, summarizing results for ten distinct parameters categorized by site group (D, I, and R) and two study periods (Table 2). The average variability, expressed as the coefficient of variation (CV), was high (30%-50%) in group D during both autumn (33.73%) and spring (36.59%), as well as in group I during the autumn (30.88%). In contrast, moderate variability (20%-30%) was observed in group R in both seasons (21.76% and 20.78%) and in group I during spring (21.79%).

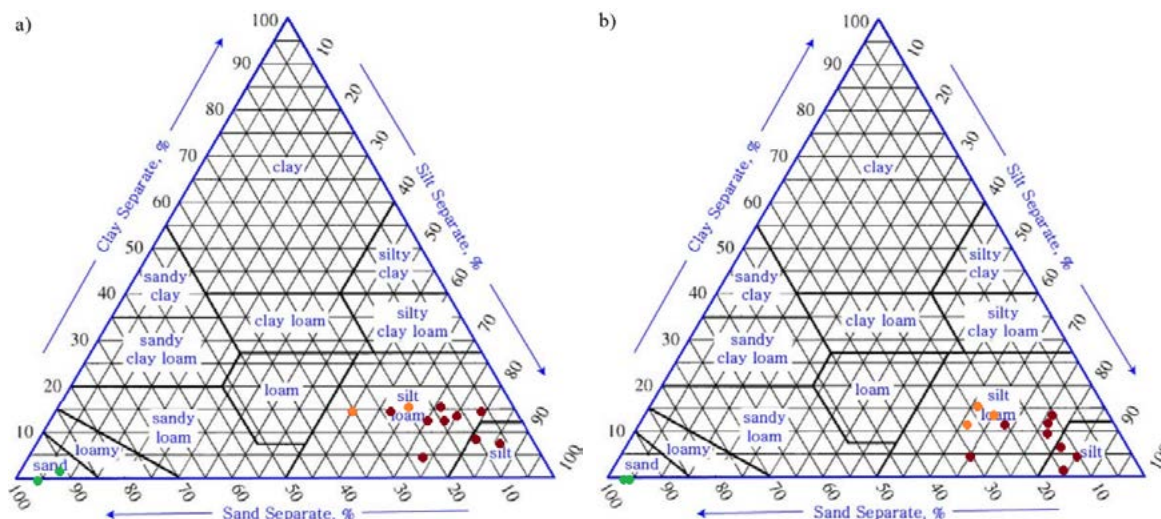
When evaluated by specific parameter, the mean CV indicated very high variability (CV > 50%) for turbidity in both autumn and spring (111.10% and 123.10%). High variability was also noted for chlorophyll a and dissolved oxygen saturation in autumn (46.95% and 30.14%), and for ammonium nitrogen (NH<sub>4</sub>-N) in spring (43.15%). In group D, the highest CVs in autumn were recorded for turbidity, dissolved oxygen saturation, dissolved oxygen, and chlorophyll a, whereas spring variability was most pronounced for turbidity, NH<sub>4</sub>-N, total dissolved solids (TDS), and electrolytic conductivity (EC). In group I, elevated variability was associated with conductivity and chlorophyll a in autumn and turbidity in spring, while group R showed significant fluctuations in turbidity, nitrate nitrogen (NO<sub>3</sub>-N), and chlorophyll a in autumn, and turbidity in spring.

Comparisons of median values between groups revealed significant spatial and seasonal disparities. In the D-I comparison during autumn, the most substantial differences were observed for turbidity, dissolved oxygen, and dissolved oxygen saturation (-75.14%, -32.65%, and -32.87%, respectively), contributing to an overall mean median difference of -12.67%. In spring, these differences were most visible in turbidity (-78.19%) and chlorophyll a (51.45%), with a mean difference of -3.44%. Generally, group D exhibited lower parameter values than group I. Differences were more pronounced in the D-R comparison. In autumn, turbidity and chlorophyll a increased sharply by 805% and 605%, respectively, while NO<sub>3</sub>-N, dissolved oxygen, and dissolved oxygen saturation decreased significantly. In spring, D-R differences were dominated by chlorophyll a (137%) and turbidity (-54.88%). The mean median differences reached 123.99% in autumn and 6.28% in spring, indicating that values in group D typically exceeded those in group R.

Finally, in the I-R comparison, autumn medians for turbidity and chlorophyll a were substantially higher in group I (3541% and 506%, respectively), while NO<sub>3</sub>-N was lower (-44.23%). Spring differences followed a similar pattern for turbidity (107%) and chlorophyll a (56.28%). With mean median differences of 393% in autumn and 13.49% in spring, concentrations were generally higher in group I than in group R. Collectively, these findings demonstrate markedly elevated levels of turbidity and chlorophyll a within the reservoir (groups D and I) compared to the Strzegomka River (group R). Table 2. Basic statistics for water quality parameters within the Dobromierz Reservoir in Poland in autumn 2023 and spring 2024, divided into groups of research points.

**Table 1.** Final classification of sediment toxicity using accepted methods and indexes.

Method	Classification				
	Class I	Class II	Class III	Class IV	Class V
Geochemical	1.00 – 1.79	1.80 – 2.59	2.60 – 3.39	3.40 – 4.19	4.20 – 5.00
LAWA					
Pollution Factor (Pi)	0.00 – 0.99	1.00 – 1.99	2.00 – 2.99	3.00 – 4.99	≥ 5.00
Nemerow Index (I <sub>N</sub> )	0.00 – 0.69	0.70 – 0.99	1.00 – 1.99	2.00 – 2.99	≥ 3.00
Geoaccumulation Index (I <sub>geo</sub> )	0.00 – 0.99	1.00 – 1.99	2.00 – 2.99	3.00 – 3.99	≥ 4.00
Contamination Factor (C <sub>f</sub> )	0.00 – 0.99	1.00 – 2.99	3.00 – 5.99	6.00 – 11.9	≥ 12.00
Ecological Risk Index (E <sub>r</sub> )	0.00 – 39.9	40.0 – 79.9	80.0 – 160	161 – 319	≥ 320



**Fig. 2.** Sediment texture within the Dobromierz reservoir in Poland: a) autumn 2023, b) spring 2024 (orange dots – direct protection zone, brown – indirect zone, green – reference points)

### Granulometric composition

Figures 2 - 5 present the granulometric composition of the collected sediments, categorized into three groups of sampling sites. The results indicate no significant differences in the proportion of skeletal and earthy fractions between sediments from the direct (D) and indirect (I) protection zones of the Dobromierz Reservoir (Figure 2). In both groups, particles <2 mm dominated, typically accounting for 98%-100% of the total mass; the sole exception was: point I1 in spring, where shells constituted the majority of the material. In contrast, sediments from reference points in the Strzegomka River (R) exhibited distinct characteristics, with a generally dominant skeletal fraction (mean: 53.75%, range 27% - 74%). These observations are further confirmed by texture analyses (Figure 3), which show no significant differences between groups D and I, with samples classified as silt loam and silt. Conversely, sediments from group R differed markedly, reflecting a higher sand content within the granulometric composition. No significant seasonal differences were observed.

The above statements are further supported by the grain-size distribution curves (Figure 4), which demonstrated that group R differs significantly from groups D and I, irrespective of season. The  $D_{50}$  values (Figure 5) corroborate this distinction, with median values of 0.073 mm for group D, 0.042 mm for group I, and 0.737 mm for group R (mean values: 0.074 mm, 0.050 mm, and 0.773 mm, respectively). According to the more detailed USDA texture classification, group D is classified as very fine sand (0.05 - 0.10 mm), group I as silt (0.002 - 0.05 mm), and group R as coarse sand (0.50 - 1.00 mm). Notably, under this classification scheme, both groups D and R fall within the sand category, despite the substantial differences observed in their granulometric characteristics.

### Heavy metals

Heavy metal concentrations in sediment samples serve as the fundamental basis for assessing toxicity using various indices; therefore, analyzing their variability across different site groups and research series is essential for a comprehensive ecological evaluation.

As shown in Figure 6a, median Cu concentrations were highest in group D, followed by group I, and lowest in group R. Seasonal trends in median values were inconsistent: concentrations decreased in spring in groups D and I by 20.29% and 5.28%, respectively, whereas group R exhibited a sharp increase of 218.33%. Furthermore, the seasonal amplitude of Cu concentrations varied significantly, with spring increases of 287.8% (10.36 mg/kg) in group D and 269.4% (26.13 mg/kg) in group I, contrasted by a reduction in group R.

Zinc displayed a comparable spatial distribution (Figure 6b), with median concentrations decreasing in the order D (127.28 mg/kg) > I (121.26 mg/kg) > R (96.78 mg/kg). As with Cu, seasonal median changes were negative in groups D and I but positive in group R, which showed a substantial spring increase of 135.08%. This rise likely reflects enhanced river discharge associated with seasonal rainfall and snowmelt. The concentration range in group D was notably higher than in all other groups. Although spring ranges in groups D and R were lower than those in autumn, group I exhibited a larger spring amplitude of 72.38 mg/kg.

Lead concentrations (Figure 6c) followed the same spatial hierarchy (D > I > R). Groups D and I showed lower median values in autumn than in spring, whereas group R exhibited a 337.5% increase during the spring. Seasonal differences in variability were pronounced in all groups, with amplitudes consistently larger ranges in spring. Group R stood out for its particularly high variability in both percentage changes and absolute values.

Cadmium (Figure 6d) exhibited the same spatial pattern, with median concentrations decreasing from group D (1.44 mg/kg) to group I (1.30 mg/kg) and group R (1.04 mg/kg). Unlike the other metals, Cd medians were higher in spring across all groups, with the most pronounced rise occurring in group R (181.82%). Seasonal fluctuations in the concentration range varied from a modest 10.00% decrease in group D to a 366.67% increase in group I, though overall variability of Cd values remained relatively similar among groups.

Chromium presented a unique spatial pattern (Figure 6e), with median concentrations ordered as I > D > R (19.00 mg/kg > 18.30 mg/kg > 14.81 mg/kg). Groups D and I exhibited

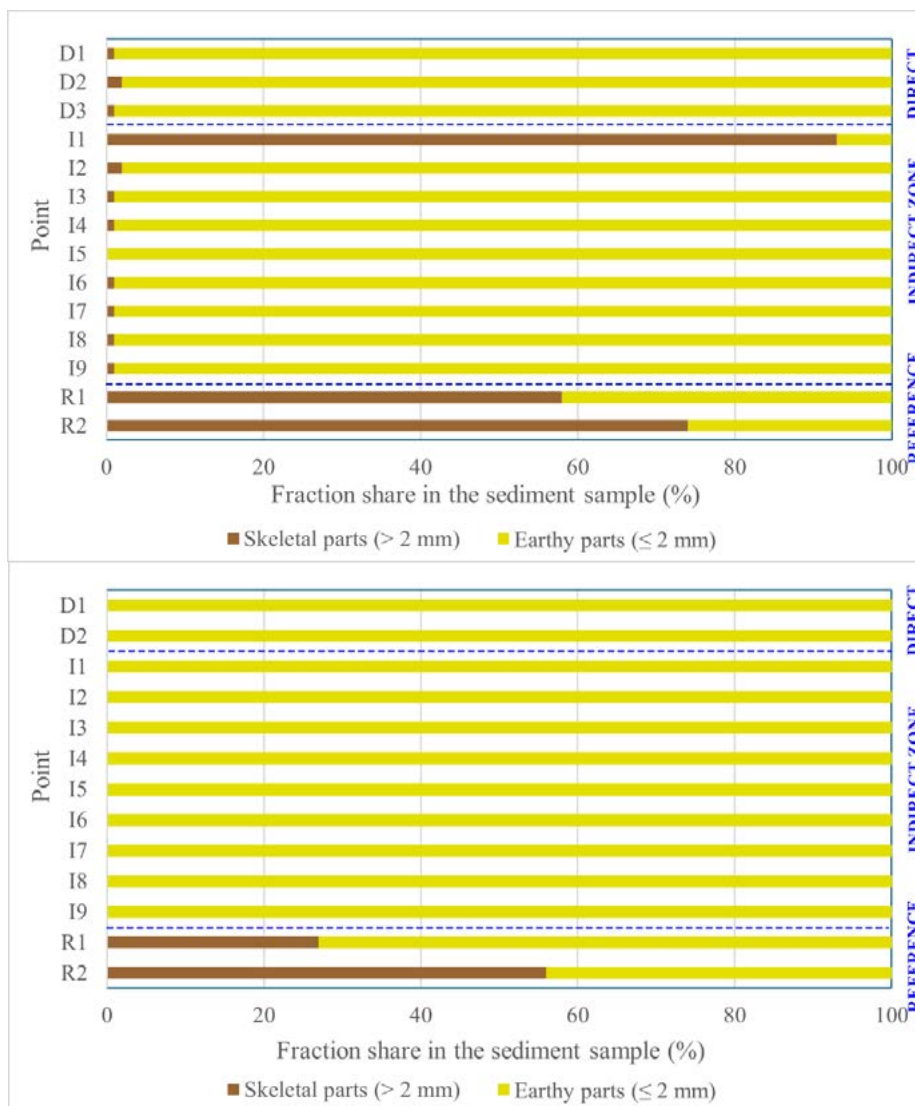


Fig. 3. The proportion of skeletal and earthy parts in bottom sediment samples from the Dobromierz reservoir in Poland (D – direct protection zone, I – indirect zone, R – reference points)

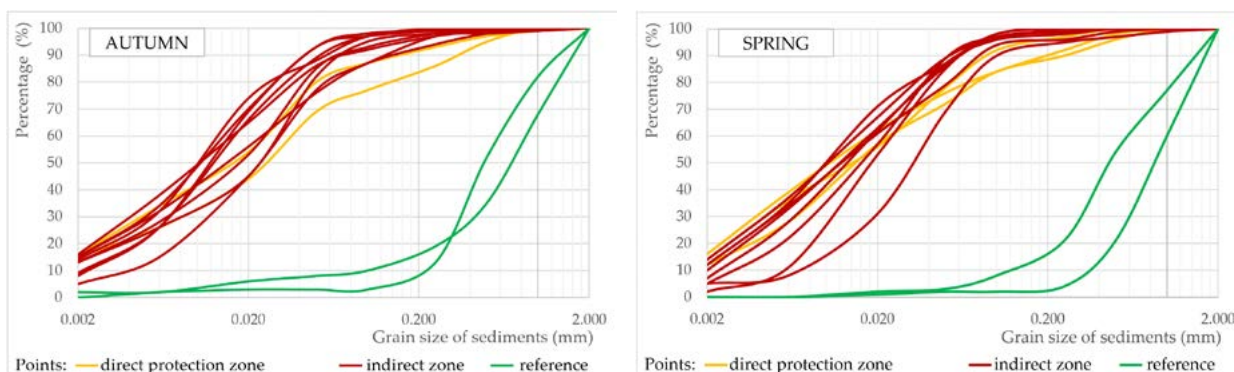
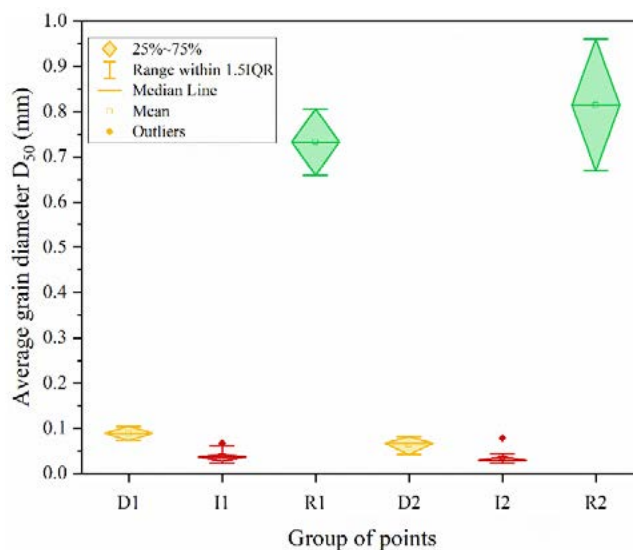


Fig. 4. Grain size distribution curves of the earthy sediments in the Dobromierz reservoir in Poland in autumn 2023 and spring 2024, divided into groups of points

lower medians in spring than in autumn, while group R showed a moderate increase of 20.25%. Seasonal amplitude changes were substantial, particularly in group I, where variability increased by 211.22%; nevertheless, no pronounced outliers were found in the overall dataset.

Nickel concentrations (Figure 6f) returned to the dominant spatial pattern of D (30.60 mg/kg) > I (27.00 mg/kg) > R (21.68 mg/kg), indicating preferential accumulation within reservoir sediments. While median concentrations in groups D and I were higher in autumn, group R exhibited significantly





**Fig. 5.** Variability of the average grain diameter ( $D_{50}$ ) of sediments within the Dobromierz reservoir (D – direct protection zone, I – indirect zone, R – reference points, 1 – autumn 2023, 2 – spring 2024)

lower autumn values (96.23%). In all groups, Ni concentration ranges were greater in spring than in autumn, with the most pronounced absolute differences observed in groups D and I. These pattern primarily reflected a higher frequency of low-concentration samples in spring, although overall variability remained consistent.

### Toxicity indices

Cross-sectional toxicity index values for sediments from the Dobromierz Reservoir, summarized in Table 3, typically fall within toxicity classes I or II on a reduced 1-5 scale when averaged across groups D, I, and R. Mean index values for these groups were 1.82, 1.65, and 1.54, respectively, corresponding to conditions of no or slight contamination. Among the analyzed metals, Cd exhibited the highest average toxicity (2.22), whereas Pb showed the lowest (1.28). Accordingly, the relative toxicity ranking of the metals was  $Cd > Cu > Ni > Cr > Zn > Pb$ . Although minor discrepancies occurred among the applied toxicity assessment methods, the aggregated results consistently remained within classes I and II. Based on their sensitivity, the methods were ranked as follows: Cf (2.53) > geochemical method (2.22) > LAWA (1.58) > Igeo (1.28) > Er (1.25) > Pi (1.17). Mean index values across site groups exhibited a convergent relationship, consistently following the spatial pattern of  $D > I > R$ . Seasonal differences in the mean values between spring and autumn were relatively minor, ranging from a 14.29% increase in Er to a 10.00% decrease in LAWA, with an overall mean difference of only 1.68%, which lies within the margin of statistical error.

A more detailed analysis of the data revealed that only the Cf index identified instances of class IV toxicity, indicating strong contamination and a potential requirement for sediment remediation, specifically for Cu and Ni in group D during autumn 2023. Remediation may also be warranted for samples classified as toxicity class III, in which accounted for 41.67% of cases using the Cf method, 36.11% in the geochemical method, 19.44% in LAWA, and 11.11% in Er. Given that these two higher toxicity classes indicate the necessity for intervention,

remediation strategies should prioritize the removal of Cd and Cu, which appeared in classes III or IV in 44.44% and 27.78% of samples, respectively. Cr and Ni constitute secondary priorities (16.67% each), whereas Zn and Pb represent the lowest concern, appearing in these categories in only 5.56% and 2.78% of samples.

### Discussion

Analysis of the water quality within the Dobromierz Reservoir reveals turbidity levels higher than those in the inflowing water, likely resulting from the resuspension of bottom sediments (Cooper et al., 2017). This resuspension makes particulate matter available to phytoplankton, contributing to the elevated chlorophyll a concentrations within the reservoir compared to the river. According to recent research (Jargal et al., 2021; Szatyłowicz and Siemaniuk, 2025), sediments serve as a reservoir for biogenic compounds; when these compounds are released into the water column, they stimulate phytoplankton growth and increase chlorophyll a levels.

The granulometric composition of bottom sediments provides critical insights into the dynamics of sediment transport, sedimentation, and pollutant retention within aquatic ecosystems (Yskak et al., 2025). Previous studies by Dąbrowska and Lejcuś (2012) indicate that sediments in the Dobromierz Reservoir are primarily clay-grained, with a high content of silicate and aluminosilicate minerals. The inlet zone, however, exhibits a higher sand fraction, a typical feature of reservoirs resulting from increased water flow velocity in these areas. As water enters the reservoir, velocity decreases, promoting sediment deposition toward the central basin and generating a sorting effect that intensifies toward the dam (Zhou et al., 2016). This granulometric profile directly influences sedimentation rates: finer grains settle more slowly, increasing the volume of suspended solids. Importantly, heavy metals preferentially associate with finer sediment fractions, such as silt and clay, due to their higher surface reactivity and adsorption capacity (Zhou et al., 2016). This pattern is supported by Yskak et al. (2025), who suggest that a predominance of sand particles

**Table 3.** Summary of toxicity index results in selected groups within the Dobromierz reservoir in Poland for the analyzed metals

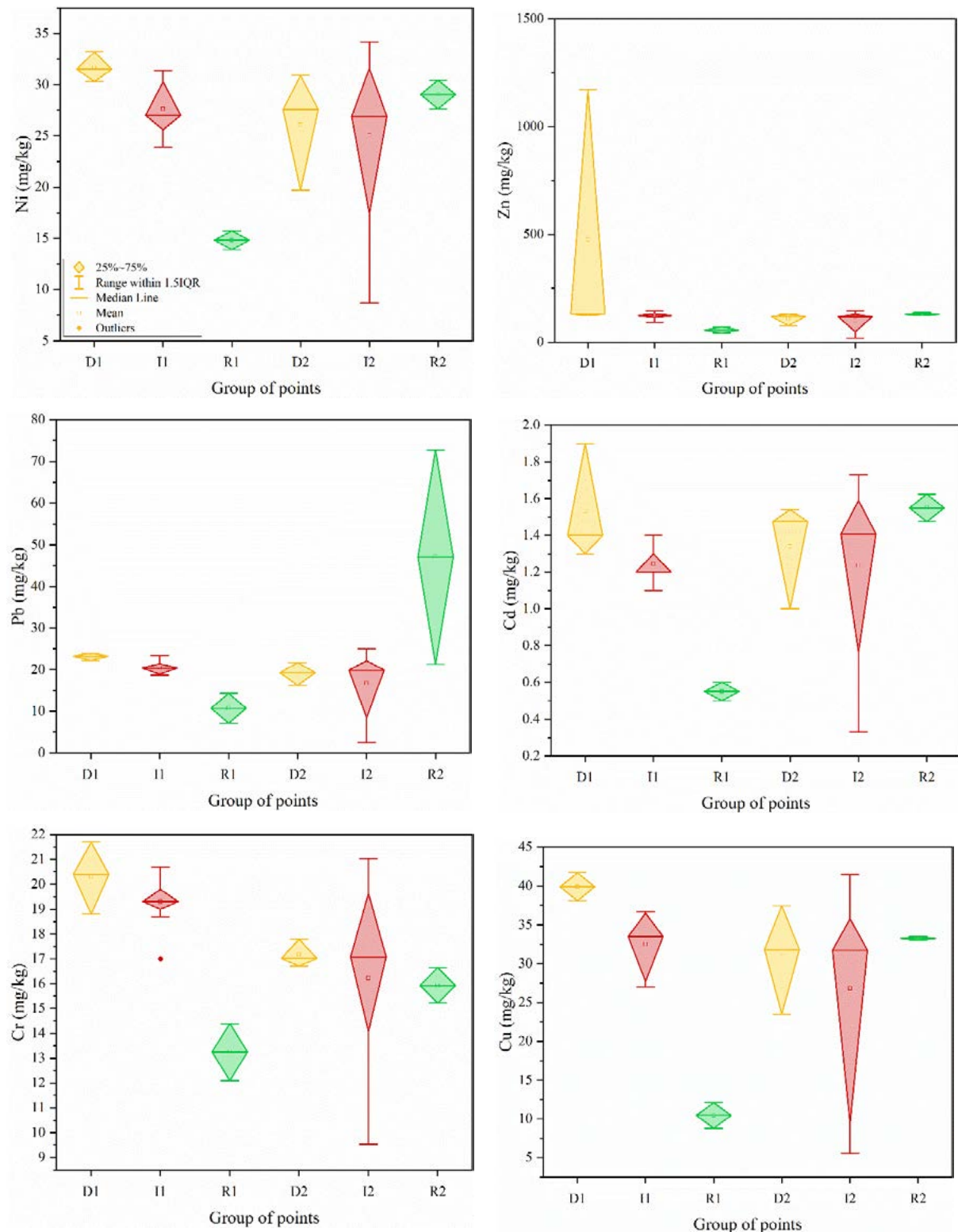
Groups of points	Parameters											
	Cu1	Cu2	Zn1	Zn2	Pb1	Pb2	Cd1	Cd2	Cr1	Cr2	Ni1	Ni2
Geochemical method												
D – direct p. z.	3.00	3.00	2.67	2.00	2.00	2.00	3.00	3.00	2.67	2.00	3.00	2.33
I – indirect p. z.	3.00	2.60	2.00	1.70	2.00	1.70	3.00	2.60	2.22	2.10	2.33	2.40
R – reference pts.	2.00	3.00	1.50	2.00	1.50	1.50	2.00	3.00	2.00	2.00	2.00	2.50
LAWA												
D – direct p. z.	2.00	2.00	2.67	1.67	1.00	1.33	3.00	2.67	1.00	1.00	2.00	1.33
I – indirect p. z.	2.00	1.70	1.89	1.70	1.00	1.00	2.44	2.70	1.00	1.00	1.33	1.40
R – reference pts.	1.00	2.00	1.00	2.00	1.00	1.50	2.00	3.00	1.00	1.00	1.00	1.50
Pollution Factor (Pi)												
D – direct p. z.	0.80	0.64	0.75	0.69	0.33	0.28	1.40	1.48	0.01	0.01	1.05	0.92
I – indirect p. z.	0.64	0.63	0.70	0.69	0.29	0.28	1.20	1.41	0.01	0.01	0.89	0.90
R – reference pts.	0.21	0.67	0.32	0.75	0.15	0.67	0.55	1.55	0.00	0.01	0.49	0.97
Geoaccumulation Index (Igeo)												
D – direct p. z.	1.33	1.06	0.55	0.50	0.47	0.39	0.56	0.59	0.82	0.68	1.26	1.11
I – indirect p. z.	1.07	1.06	0.51	0.50	0.41	0.40	0.48	0.56	0.77	0.69	1.08	1.08
R – reference pts.	0.35	1.11	0.23	0.55	0.22	0.94	0.22	0.62	0.53	0.64	0.59	1.17
Contamination Factor (Cf)												
D – direct p. z.	6.65	5.30	2.75	2.51	2.32	1.93	2.80	2.95	4.08	3.40	6.30	5.51
I – indirect p. z.	5.35	5.29	2.54	2.50	2.03	1.99	2.40	2.82	3.85	3.42	5.36	5.38
R – reference pts.	1.74	5.54	1.16	2.72	1.08	4.70	1.10	3.10	2.65	3.19	2.96	5.81
Ecological Risk Index (Er)												
D – direct p. z.	33.25	26.50	2.75	2.51	11.60	9.63	84.00	88.50	8.16	6.80	31.50	27.57
I – indirect p. z.	27.92	26.44	2.58	2.50	10.20	9.96	72.00	84.45	7.72	6.83	27.00	26.91
R – reference pts.	8.71	27.72	1.16	2.72	5.38	23.52	33.00	93.00	5.30	6.37	14.80	29.04

(0.05–2 mm) corresponds to moderate heavy metal retention, whereas Zhou et al. (2016) demonstrate that the highest accumulation of heavy metals occurs in the most dispersed particles, specifically those smaller than 0.01 mm.

In examining heavy metal concentrations in the Dobromierz Reservoir sediments, the elevated Cu values observed in group R during spring relative to autumn are of particular note. As a trace element, Cu exhibits a high degree of mobility between water and sediments and can be remobilized under extreme conditions such as intense rainfall, leading to precipitation or resuspension (Jordache et al., 2022). This seasonal variability, influenced by heavy precipitation and increased river flow, is consistent with observations of Souza et al. (2016) and Jordache et al. (2022), who reported strong correlations between altitude and concentrations of metals such as Cu and Zn in March, suggesting that spring river flow velocity is a key factor controlling metal levels. Comparable patterns have been reported in other reservoirs. Yuan et al. (2020) found that heavy metals such as Cr, Cu, Mn, and Zn tended to accumulate in the lower reaches of a Chinese river. Conversely, Ao et al. (2024) observed higher concentrations of metals such as Cr, Pb, Cu, Zn, As, Ni, and Co in the upper sections of the reservoir-fed river. Their study indicated that, while seasonal fluctuations were not significant for these metals, concentrations were generally higher at the river mouth compared to open water areas.

Sediments of the Dobromierz Reservoir exhibit the highest contamination levels in Cu and Ni, likely resulting from a combination of atmospheric deposition, municipal waste storage, coal combustion, and agricultural runoff. Local domestic coal use is a particularly significant contributor, as it contains high concentrations of these metals that accumulate in surrounding soils and water following combustion (Chen et al., 2023). Situated within a submontane agricultural catchment, the reservoir is highly susceptible to rainfall-driven pollutant transport (Dąbrowska et al., 2018). This pressure is further amplified by runoff from fertilized fields and the discharge of untreated or poorly managed municipal sewage, such as septic tank leakages, into the aquatic system (Szewczyk et al., 2025). Additionally, the widespread use of transport fuels and coal-based energy products in the Dobromierz commune contributes to atmospheric metal deposition in the region (Kulikowski, 2022).

Even at moderate concentrations, these heavy metals pose significant risk to human health and overall water quality, with potential effects ranging from metabolic disorders to stunted growth, or mortality in aquatic organisms (Chen et al., 2023). Consequently, implementing effective remediation strategies is essential for mitigating these risks. One ex-situ approach is stabilization using nanotechnology, specifically zero-valent iron nanoparticles (nZVI), which are valued for their high

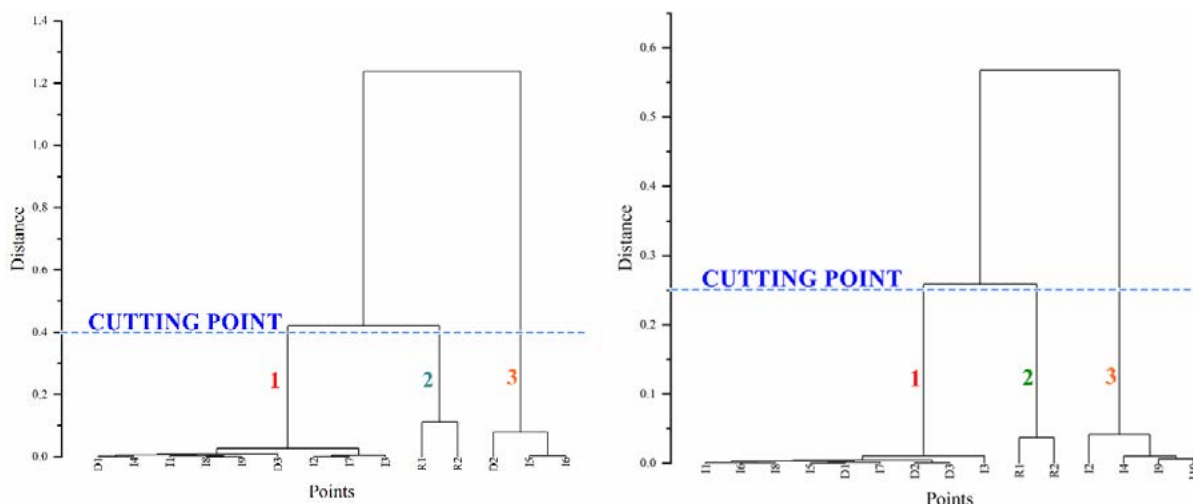


**Fig. 6.** Variability of heavy metal concentrations in bottom sediments within the Dobromierz reservoir (D – direct protection zone, I – indirect zone, R – reference points, 1 – autumn 2023, 2 – spring 2024): a) Cu, b) Zn, c) Pb, d) Cd, e) Cr, f) Ni

reactivity and specific surface area (Zhao et al., 2016; Gil-Diaz et al., 2020). Recent developments have enhanced this method by combining nZVI with biologically active extracts from oak and mulberry leaves, which effectively convert available Cu and Ni into stable, non-toxic fractions (Slijepčević et al., 2020). This approach can increase the residual proportion of stabilized Cu and Ni by up to 81%. However, the method is associated with substantial costs. For a reservoir with a 400,000

m<sup>3</sup> capacity, investment expenses reach €17.3/m<sup>3</sup>, with annual operating costs exceeding €50/m<sup>3</sup>, primarily due to landfilling and storage requirements. Identifying a beneficial secondary use for the stabilized material remains the most practical strategy to offset these costs (Slijepčević et al., 2020).

An alternative strategy involves in-situ remediation using phosphate-based binders such as Na<sub>3</sub>PO<sub>4</sub>, NaH<sub>2</sub>PO<sub>4</sub>, and Na<sub>2</sub>HPO<sub>4</sub> (Du et al., 2014). These compounds immobilize toxic



**Fig. 7.** Hierarchical Cluster Analysis for the obtained results, divided into sediment sampling points within the Dobromierz reservoir in Poland (D – direct protection zone, I – indirect zone, R – reference points): a) heavy metals and D50, b) toxicity indices

metals by forming stable complexes that resist dissolution, even under acidic conditions (Bilal et al., 2023). While generally considered a cost-effective and environmentally friendly approach to reducing bioavailability, their effectiveness can be variable (Xu et al., 2024). Some studies suggest that certain phosphate binders may actually lead to increased leaching of Cu and Ni through the formation of soluble metal-phosphate complexes, highlighting the need for careful selection based on the specific geochemical environment of the reservoir.

Ultimately, selecting an appropriate remediation strategy requires balancing financial feasibility, environmental impact, and the site's technical constraints. Given the significant costs associated with active cleanup, prioritizing preventative measures is the most practical approach. Local authorities should focus on controlling pollution at its sources by enforcing stringent waste management practices and regulating domestic fuel combustion. Prohibiting the direct discharge of sewage and municipal waste into the reservoir is essential. Furthermore, the use of pesticides and fertilizers in surrounding agricultural areas should be carefully managed to minimize the influx of heavy metals via surface runoff (Chen et al., 2023; Szewczyk et al., 2025).

### Comparison of sediment properties between groups

The hierarchical cluster analysis (HCA) performed for metals and  $D_{50}$  results in sediments (Figure 7a) indicates the identification of three clusters: the first contains points located in groups D (D1, D3) and I (I1-I4, I7-I9); the second contains points from group R (R1, R2); and the third contains points from groups D (D2) and I (I5, I6). This demonstrates, at a general level, that the properties of sediments in the direct and indirect protection zones of the Dobromierz Reservoir do not differ notably, whereas sediments collected from the Strzegomka River exhibit greater variability and form a separate cluster. This observation is further supported by earlier analyses.

The second HCA, performed for toxicity indices (Figure 7b), also confirms these findings, indicating similarity among points from groups D and I located in the Dobromierz Reservoir and distinct results for points from group R located in the Strzegomka River. The first cluster contains points from

groups D (D1, D2, D3) and I (I1, I6, I8, I5, I7, I3); the second cluster contains only points from group R (R1, R2); and the third cluster contains points from group I (I4, I9, I10).

### Conclusions

Granulometric analysis confirmed that earthy fractions dominate groups D and I, which explains the higher toxicity observed in sediments within the indirect (I) and direct (D) protection zones compared to the reference (R) zone. The prevalence of these finer particles enhances the sorption capacity of the sediment matrix, rendering it more susceptible to the adsorption of heavy metals.

The elevated metal concentrations found in group R during the spring are attributed to increased river discharge driven by seasonal rainfall and snowmelt. These hydrological dynamics result in higher metal levels at points upstream of the reservoir, while leading to lower concentrations within the reservoir itself. Furthermore, under extreme weather conditions, heavy rainfall can induce resuspension, which may cause metals to precipitate. In contrast, metals exhibit a more pronounced tendency to accumulate in reservoir sediments during the autumn months.

Toxicity index values for sediments collected from the Dobromierz Reservoir typically fall within toxicity classes I, II, or III, signifying slight or no contamination. Based on the calculated mean index values, the hierarchy of metals from most toxic to least toxic is as follows:  $Cd > Cu > Ni > Cr > Zn > Pb$ . Hierarchical cluster analysis (HCA) of metal concentrations and toxicity indices demonstrates that sediment properties in the direct and indirect protection zones (groups D and I) do not differ significantly, whereas sediments collected from the Strzegomka River (group R) exhibit markedly greater variability.

Broader analyses incorporating both sediment granulometric characteristics and toxicity indices serve as a valuable tool for assessing contamination levels, providing practical guidance for effective water resource management. It is therefore essential for local authorities to monitor and limit pollution sources while simultaneously raising environmental awareness. Such integrated actions are necessary to ensure

the long-term environmental protection of drinking water reservoirs.

Future research applying these granulometric and toxicological frameworks should be expanded to include a larger number of sample series and a broader range of reservoirs. Such efforts will facilitate more accurate conclusions and help to fill existing research gaps in the field of aquatic sedimentology.

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## Zintegrowana ocena zanieczyszczenia metalami ciężkimi i ryzyka ekologicznego w osadach dennych zbiornika wody pitnej Dobromierz w Polsce

**Streszczenie.** Celem pracy była ocena stopnia zanieczyszczenia metalami ciężkimi (Cu, Zn, Pb, Cd, Cr, Ni) oraz potencjalnego zagrożenia ekologicznego osadów dennych zbiornika wody pitnej Dobromierz (Polska). Badania obejmowały pobranie próbek w bezpośredniej i pośredniej strefie ochronnej zbiornika oraz w punktach referencyjnych na rzece Strzegomce w ciągu dwóch sezonów (jesień 2023, wiosna 2024). Analizy laboratoryjne wykonano metodą ICP-OES po mineralizacji próbek w wodzie królewskiej, a do oceny toksyczności wykorzystano zintegrowane wskaźniki: podejście geochemiczne, LAWA, Pi, Igeo, Cf i Er. Uzyskane wyniki wskazują, że dominującą frakcją osadów w zbiorniku są części ziemiste (<2 mm), które sprzyjają akumulacji metali ciężkich. Najwyższe mediany stężeń metali odnotowano w strefie ochrony bezpośredniej, co potwierdzają wartości wskaźników toksyczności. Kolejność toksyczności metali była następująca: Cd > Cu > Ni > Cr > Zn > Pb. Osady zostały w większości zaklasyfikowane do klasy toksyczności I–II (lekkie lub umiarkowanie zanieczyszczone), ale w kilku miejscach (Cu, Ni) konieczna byłaby remediacja. Analiza skupień potwierdziła podobieństwo właściwości osadów w strefach ochronnych zbiornika i ich różnice w porównaniu z próbkami z rzeki Strzegomki. Wyniki podkreślają znaczenie kompleksowych, wielowskaźnikowych metod oceny w diagnozowaniu ekotoksyczności osadów dennych w zbiornikach wody pitnej. Niniejsze badanie wypełnia lukę w wiedzy na temat zanieczyszczenia metalami ciężkimi w Polsce i stanowi podstawę do wdrażania środków zaradczych oraz zrównoważonego zarządzania zasobami wodnymi.