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Heavy metals toxicity assessment in water and bottom sediments of two tourist lakes of different origin near Gorzów Wielkopolski (western Poland)

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Abstract. Lake tourism includes activities both within the lake itself and in its immediate surroundings. These activities may lead to a range of changes in lake ecosystems, including an increased input of pollutants. Among the most important and still widely studied pollutants are heavy metals (HMs), whose concentrations and potential toxicity were investigated in the waters and bottom sediments of two lakes of different origin near Gorzów Wielkopolski: the natural Kłodawskie Lake and the gravel pit lake Karnin Reservoir. HM concentrations were determined using inductively coupled plasma triple quadrupole mass spectrometry (ICP-QQQ-MS). The results obtained for HMs in water were analyzed in terms of potential toxic effects on humans, whereas HMs in bottom sediments were assessed in terms of their potential toxicity to aquatic biota. The results indicate comparable HM concentrations in the waters of both lakes and show no potential non-carcinogenic and carcinogenic health risk for humans, both in terms of chronic dermal exposure and quantitative assessment. In contrast, HM concentrations in bottom sediments differed significantly between the lakes, with notably higher values recorded in Kłodawskie Lake. The assessment of individual HMs using the modified hazard quotient (mHQ) indicated very low toxicity for Pb and Zn, and to a lesser extent for Cd, Cu, and Ni. Integrated indices indicated no potential combined toxicity of HMs. The presented study provides a basis for conducting similar analyses in lakes used for recreational purposes and highlights the potential of gravel pit lakes for tourism, particularly in regions characterized by a low number of natural lakes.

Keywords: gravel pit lake, cancer health risk, limnotourism, toxicity indices, suburban lakes.

Introduction

Progressing climate change increasingly leads to the occurrence of extreme heat events in Europe, which are becoming one of the most significant climate-related hazards for humans (Cvijanovic et al., 2023; Wrona, 2024; Sun et al., 2025). Heat waves are particularly pronounced in cities, where the development of the urban heat island occurs (Krüger et al., 2023; Yadav et al., 2023). This phenomenon leads to a deterioration of thermal comfort among urban residents and increases the demand for spaces that provide cooling and regeneration in natural environments (Bowler et al., 2010; Twardosz, 2023). Consequently, especially during the summer season, urban residents increasingly engage in lake tourism (Duda-Gromada, 2009; Borkowski & Tritt, 2023), also referred to as limnotourism (Młynarczyk & Borkowski, 2015). Lake tourism is a form of tourism associated both with the lake itself and with its surrounding areas, encompassing all types of tourism and recreational activities undertaken on the lake as well as on the adjacent land areas

(Duda-Gromada, 2009). According to the research of Skowron (2023), the bathing season in Poland usually begins between 20 and 25 May and ends in the second half of September, providing an average of 69 days of bathing season. A common destination for lake tourism for urban populations seeking cooling and recreation is urban and suburban lakes, which offer numerous attractions for both children and adults (Godlewski et al., 2023). However, intensive tourist use may lead to a significant increase in anthropogenic pressure on lakes, including shoreline transformation, disturbance of aquatic biota habitat balance and a decline in biodiversity, as well as an increased input of pollutants into the environment (Gössling, 2002; Dokulil, 2014; Sun & Liu, 2020; Pásková et al., 2024).

One of the most important and still among the most frequently studied pollutants in surface waters are heavy metals (HMs) (e.g., Sojka et al., 2018, 2019a, 2019b; Jaskuła et al., 2026; Szewczyk et al., 2026; Śniady et al., 2026). They may pose significant non-carcinogenic and carcinogenic risks to humans (Budi et al., 2024), and may also substantially affect biodiversity (Sharma et al., 2025). Potential sources of HMs in lakes used for tourism and their immediate surroundings include boat and watercraft traffic, increased road traffic, activities associated with camping sites and recreational resorts, construction and expansion of infrastructure, as well as littering by visiting tourists (Mosisch & Arthington, 1998; Sun & Liu, 2020; Pásková et al., 2024).

Among approximately 6,800 lakes present in Poland, the majority are natural lakes (Skowron, 2023). Additionally, intensive exploitation of resources and the increasingly popular water-based reclamation direction led to the formation of a growing number of artificial water bodies (Pietrzykowski & Krzaklewski, 2018). The most important examples include pit lakes within the Adamów lignite mine district (Marszelewski et al., 2017; Śniady et al., 2024b), the Konin lignite mine district (Marszelewski, 2023), and the Upper Silesian Anthropogenic Lake District (Rzętała & Jaguś, 2012). Additionally, it should be emphasized that reclaimed open pits frequently include those formed after the extraction of clay, sand, and gravel (e.g., Gołdyn et al., 2006; Stępniewska & Abramowicz, 2016; Hetmański et al., 2023), although they are still insufficiently studied. Some authors indicate that HMs may be released from sands and gravels into waters in such newly formed pit lakes (e.g., Ogbuagu & Samuel, 2014; Liu et al., 2025), whereas Hetmański et al. (2023), for example, pointed out that gravel pit lakes may constitute important sites for nature conservation, including the creation of new habitats. Artificial lakes may also serve as significant destinations for lake tourism, particularly in regions characterized by a low number of natural lakes (Dulias, 2010; Fagiewicz, 2013).

Therefore, this study presents an analysis of two suburban lakes of different origins, namely a natural lake and a gravel pit lake located near Gorzów Wielkopolski. The specific objectives of this study are: (1) to analyze the concentrations of HMs in the water and bottom sediments of two suburban lakes near Gorzów Wielkopolski; (2) to assess the potential non-carcinogenic and carcinogenic impact of HMs in water on humans; (3) to evaluate the potential toxicity of HMs in the bottom sediments of these lakes for aquatic biota; and (4) to attempt to assess the influence of lake origin on HM concentrations in these lakes.

Materials and methods

Research area

Gorzów Wielkopolski is a city located in western Poland, inhabited by slightly more than 100,000 residents. Studies conducted by Marciniak (2024) indicate that there are no major lakes within the city limits of Gorzów Wielkopolski that could be used for tourism. Consequently, residents are required to travel to suburban lakes to engage in lake tourism. In the present study, two such lakes frequently visited by inhabitants of Gorzów Wielkopolski were analyzed: Kłodawskie Lake and Karnin Reservoir (Fig. 1).

Kłodawskie Lake is located in the village of Kłodawa, near Gorzów Wielkopolski (Fig. 1), within the Gorzów Plain mesoregion (Solon et al., 2018). It is a natural postglacial lake of elongated shape, with a surface area of approximately 0.28 km^2 (Tab. 1). The lake is closed (endorheic) and is primarily supplied by waters from its own catchment. The maximum depth recorded during the present study was 16 m. For centuries, Kłodawskie Lake was used for fisheries and fishery management (Gaziński, 2003). However, intensive urbanization of areas surrounding Gorzów Wielkopolski, along with the development of the village of Kłodawa, led to a shift in the lake's function from fishery use to recreation. Currently, Kłodawskie Lake constitutes an important recreational site for both city and village residents. As a result, infrastructure such as a beach, water equipment rental facilities, a wake park, and numerous piers for anglers and visitors have been developed.

Karnin Reservoir is a pit lake located in the village of Karnin, near Gorzów Wielkopolski (Fig. 1), within the Gorzów Basin mesoregion (Solon et al., 2018). It is a relatively young pit lake of regular shape, formed in the area of a former open-pit gravel mine in the 1990s. The surface area of Karnin Reservoir is 0.26 km^2 and the maximum depth recorded during this study was 7.8 m (Tab. 1). The pit lake was created for recreational purposes, which involved artificial fish stocking and the development of a beach area. The beach is equipped with various tourist facilities, including football and volleyball fields, piers, water equipment rentals, barbecue shelters, and a promenade. Consequently, Karnin Reservoir attracts a large number of visitors, especially during the summer season.

Table 1. Morphometric and hydrological parameters of the studied lakes

Parameter	Kłodawskie Lake	Karnin Reservoir
Origin	natural, post-glacial	artificial, post-gravel extraction
Area [km^2]	0.28	0.26
Length [km]	1.76	0.65
Width [km]	0.26	0.64
Shoreline length [km]	4.06	2.16
Maximum recorded depth [m]	16.00	7.80
Hydrological type	endorheic	endorheic

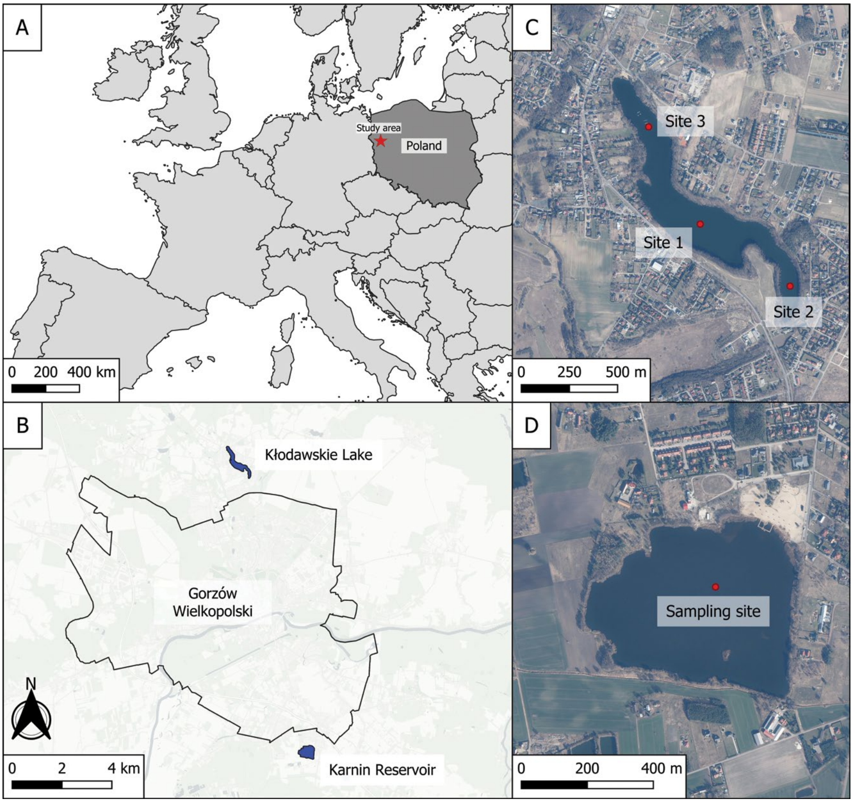

Fig. 1. Location of the study area in Europe (A), detailed location of the studied lakes near Gorzów Wielkopolski (B), and orthophotomaps of the studied lakes: Kłodawskie Lake (C) and Karnin Reservoir (D)

Sample collection and preparation

The sample collection took place on 6-7 August 2024, from Kłodawskie Lake and the Karnin Reservoir. The summer sampling period was chosen due to the ongoing lake tourism season in Poland at the time (Skowron, 2023). A total of 8 water samples and 3 sediment samples were collected from Kłodawskie Lake across 3 sampling sites, due to the lake's great length, which may result in reduced water mixing in narrower areas (Gierszewski et al., 2015; Sojka et al., 2019a). From the Karnin Reservoir, 3 water samples and 1 sediment sample were collected from the deepest site in the central part of the reservoir, selected for its good wind exposure and regular shape, which promotes thorough mixing of the reservoir's waters (Śniady et al., 2024b). Water Sampler USB 50015 (UWITEC GmbH, Mondsee, Austria) was used to collect water samples. The samples were placed in 250 ml polyethylene bottles (HDPE) by Nalgene® and preserved *in situ* with HNO_3 (Merck, Darmstadt, Germany) to a pH <2. After collection, the samples were transported to a chemical laboratory in a mobile refrigerator at a temperature of about 4 ± 2.5°C. Adequate precautions were taken to prevent contamination of the water samples during collection, transport, and handling.

Sediment samples were collected using an Ekman sediment grab, with the top layer of sediment placed into zip-lock bags. To prepare the samples for further analysis, they were then dried at 105°C using a drying oven (Digitheat, J.P. Selecta, Spain), disaggregated and homogenized by grinding in an agate mortar prior to extraction. HMs were extracted using 1:4 HCl to determine labile fractions characterized by high mobility and bioaccumulation potential in the aquatic environment (Snape et al., 2004; Pasieczna, 2012; Śniady et al., 2024a, 2024b; Jaskuła et al., 2026). The samples were extracted using the MARS 5 Xpress (CEM, Matthews, NC, USA) microwave digestion system. Additionally, *in situ* measurements of basic water parameters such as pH, temperature, optical dissolved oxygen (ODO), electrical conductivity (EC), total dissolved solids (TDS), and redox potential (Eh) were conducted using a ProDSS Multiparameter Digital Water Quality Meter by YSI (Ohio, USA).

Chemical analysis

Concentrations of HMs (Cd, Cr, Cu, Ni, Pb, Zn) were determined using inductively coupled plasma triple quadrupole mass spectrometry (ICP-QQQ-MS; 8800 Triple Quad, Agilent Technologies, Tokyo, Japan). Details of the analytical procedure and instrument settings are provided in Table 2 and Siepak et al. (2023) and Sojka et al. (2024). All reagents used during the analysis were of trace metal grade, and the water was deionized to a resistivity of 18.2 MΩ·cm using a Direct-Q® UV3 Ultrapure Water System (Millipore, France). Quality control was performed using certified reference materials (CRM), namely SRM no. 1640a (National Institute of Standards and Technology, Gaithersburg, MD, USA) for water and LGC no. 6187 (Manchester, England) for bottom sediments. High compliance with reference values was achieved (Tab. 3).

Table 2. ICP-QQQ-MS operating conditions

Spectrometer	Agilent 8800 Triple Quad
Nebulizer	MicroMist
Interface	Sampler and skimmer cones in Ni
RF power	1550 W
RF matching	1.80 V
Plasma flow rate ($L \cdot min^{-1}$)	15
Carrier gas flow ($L \cdot min^{-1}$)	1.08
Nebulizer pump (rps)	0.3
Spray chamber	Scott type – double pass
Spray chamber temp (°C)	2
Sample depth (mm)	8.0
Gas flow rate	He 5.0 ($mL \cdot min^{-1}$)
Internal standard	^{72}Ge, ^{89}Y, ^{115}In, ^{125}Te, and ^{191}Ir

Table 3. Comparison of certified mass concentration, determination value, and recovery for analyzed elements

Waters				Bottom sediments			
Element	Certified value [µg/L]	Determination value [µg/L]	Recovery (%)	Element	Certified value [mg/kg]	Determination value [mg/kg]	Recovery (%)
CRM 1640a				CRM LGC 6187			
Cd	3.992 ± 0.074	3.657 ± 0.055	91.6	Cd	2.7 ± 0.3	2.6 ± 0.3	96.3
Cr	40.54 ± 0.30	41.69 ± 0.14	102.8	Cr	84.0 ± 9.4	84.1 ± 3.5	100.1
Cu	85.75 ± 0.51	84.01 ± 0.43	98.0	Cu	83.6 ± 4.1	84.6 ± 1.0	101.2
Ni	25.32 ± 0.14	26.19 ± 0.09	103.4	Ni	34.7 ± 1.7	33.2 ± 0.9	95.7
Pb	12.101 ± 0.050	12.288 ± 0.033	101.5	Pb	77.2 ± 4.5	75.9 ± 1.5	98.3
Zn	55.64 ± 0.35	55.22 ± 0.22	99.2	Zn	439 ± 26	441 ± 6.7	100.5

Heavy metals toxicity assessment in water

To assess the potential non-cancer health risk associated with dermal absorption of HMs through the skin, hazard quotients (HQ_i) and the hazard index (HI) were calculated (USEPA, 2004; Mohammadi et al., 2019; Zakir et al., 2020). For this purpose, the chronic daily intake for dermal absorption (CDI_{dermal}) was first calculated according to the following equation (USEPA, 2004):

$$CDI_{dermal} = \frac{C_w \times SA \times K_p \times ET \times EF \times EP \times CF}{BW \times AT}$$

where C_w is the HMs concentration [mg/L], SA is the skin surface area [cm^2], K_p is the permeability coefficient [cm/hour], ET is the exposure time [hour/event], EF is the exposure frequency [days/year], EP is the exposure duration [years], CF is the conversion factor [L/cm^3], BW is body weight [kg], and AT is the averaging time [days]. The values adopted for the calculations were: SA = 18,000 cm^2, ET = 5 hours/event, EP = 30 years, CF = 0.001 L/cm^3, BW = 70 kg, ABS = 0.001, and AT = 10,950 days. The K_p values depended on the metal and were assumed as 0.001 (Cd, Cu, Pb), 0.002 (Cr), 0.006 (Zn), and 0.0002 (Ni) (USEPA, 2004; Mohammadi et al., 2019). The EF value was adjusted to the purpose of the study and assumed to be 69 days/year, corresponding to the duration of the bathing season in Poland according to Skowron (2023).

The CDI_{dermal} values calculated in this way were then used to determine the hazard quotients (HQ_i) according to the following equation:

$$HQ_i = \frac{CDI_{dermal}}{RfD}$$

where RfD is the reference dose and, for the dermal exposure pathway, equals (all in mg/kg/day): 0.000005 for Cd, 0.000015 for Cr, 0.012 for Cu, 0.0054 for Ni, 0.00042 for Pb, and 0.06 for Zn (Mohammadi et al., 2019).

In the final step, to assess the total potential non-carcinogenic health risks caused by different HMs present in the waters, the hazard index (HI) was calculated according to the following equation:

$$HI = \sum_{i=1}^{n} HQ_i = HQ_{Cd} + HQ_{Cr} + HQ_{Cu} + HQ_{Ni} + HQ_{Pb} + HQ_{Zn}$$

It is assumed that when HI > 1 there is a risk of non-carcinogenic impacts for bathers, whereas when HI < 1 there is no significant health risk (Mohammadi et al., 2019).

Subsequently, a screening-level carcinogenic risk for dermal exposure was estimated using the incremental lifetime cancer risk (ILCR) approach. ILCR represents the incremental probability of developing cancer over a lifetime, assumed to be 70 years, as a result of exposure to a specific carcinogenic element (USEPA, 2004; Mohammadi et al., 2019). The screening-level ILCR for dermal exposure during recreational bathing was calculated according to the following equation:

$$ILCR = LADD_{dermal} \times CSF$$

where $LADD_{dermal}$ is the lifetime average daily dose for dermal exposure, calculated using the same equation as CDI_{dermal}, but with the averaging time adjusted to carcinogenic risk, i.e. AT = 25,550 days (70 years × 365 days/year). CSF denotes the cancer slope factor, with values of 0.0085 kg/mg/day for Pb, and 10.8 kg/mg/day for Cr (USEPA, 2004; IRIS, 2025). The acceptable risk levels were assumed to be 10^{-6} for a single carcinogenic element and $<10^{-4}$ for the summed multi-element carcinogenic risk (Tepanosyan et al., 2017).

Additionally, to quantitatively determine the concentrations of HMs that may cause potential health effects, the heavy metal toxicity load (HMTL) developed by Saha & Paul (2019) was applied. It is calculated by multiplying the studied metal concentration in water (C_i, mg/L) by its total hazard score (HIS_i) assigned in the Substance Priority List prepared by the Agency for Toxic Substances and Disease Registry (ATSDR, 2022), according to the following equation (Saha & Paul, 2019; Śniady et al., 2025):

$$HMTL = \sum_{i=1}^{n} C_i \times HIS_i$$

The scale for assessing potential toxicity was adopted from Yakovlev et al. (2022).

Heavy metals toxicity assessment in bottom sediments

For HM concentrations in bottom sediments, the potential impact on aquatic biota in the studied lakes was assessed. For this purpose, three indices of potential toxicity were calculated: modified hazard quotient (mHQ), mean effects range-median quotient (mERMQ), and toxic risk index (TRI). The first of these, the modified hazard quotient (mHQ), proposed by Benson et al. (2018), is used to assess the potential toxicity of individual HMs and is calculated according to the following equation:

$$mHQ = \left[C_i \left(\frac{1}{TEL} + \frac{1}{PEL} + \frac{1}{SEL}\right)\right]^{\frac{1}{2}}$$

where C_i denotes the HM concentration in the sediment [mg/kg], while TEL, PEL, and SEL represent the threshold effect level [mg/kg], probable effect level [mg/kg], and severe effect level [mg/kg], respectively. The scale for assessing potential toxicity was adopted from Benson et al. (2018).

The second index, the mean effects range-median quotient (mERMQ), is used for the integrated assessment of the toxicity of HMs and is calculated in two steps according to the following equations (Wang et al., 2020; Liao et al., 2022):

$$ERMQ_i = \frac{C_i}{ERM_i}$$

$$mERMQ = \frac{\sum_{i=1}^{n} ERMQ_i}{n}$$

where C_i denotes the HM concentration in the sediment [mg/kg], ERM represents the effects range-median [mg/kg], and n denotes the number of compounds. The scale used to assess potential toxicity was adopted from Liao et al. (2022).

The last of the applied indices, the toxic risk index (TRI), was developed by Zhang et al. (2016) and is calculated according to the following equation:

$$TRI = \sum_{i=1}^{n} \sqrt{\frac{\left(\frac{C_i}{TEC_i}\right)^2 + \left(\frac{C_i}{PEC_i}\right)^2}{2}}$$

where C_i denotes the concentration of the analyzed HM in the sediment [mg/kg], TEC stands for threshold effect concentration [mg/kg], and PEC refers to probable effect concentration [mg/kg]. The toxicity assessment scale was adopted from Zhang et al. (2016). The values of TEL, PEL, SEL, ERM, TEC, and PEC were adopted from MacDonald et al. (2000).

Results

Basic physico-chemical parameters

Physico-chemical parameters indicate the presence of a well-developed thermal stratification at the time of sampling in both studied lakes (Fig. 2). A distinct epilimnion is observed down to a depth of approximately 4 m, whereas below this depth most parameters decrease, with the exception of TDS. Surface water temperature in the studied lakes exceeded 23 °C, while it decreased with depth, reaching a minimum value of 6.2 °C at the deepest site of Kłodawskie Lake. In general, anoxic conditions prevailed below 4 m in both lakes, accompanied by a transition from oxidizing conditions in surface waters to reducing conditions in the deeper parts of the water column. The pH of the studied lakes was generally alkaline at the surface, decreasing to near-neutral conditions in the deeper parts of Karnin Reservoir and at Site 3 of Kłodawskie Lake. Slightly acidic pH values were observed only near the bottom at Sites 1 and 2 of Kłodawskie Lake.

The highest EC among the studied pit lake was recorded in Karnin Reservoir, ranging from 513 to 555.7 µS/cm. In Kłodawskie Lake, EC values were lower, ranging from 360.1 to 478.5 µS/cm, with the lowest values occurring at a depth of approximately 10 m. In contrast to EC, TDS shows an increasing trend with depth in all lakes. However, similarly to EC, the highest TDS values were recorded in Karnin Reservoir, reaching up to 438 mg/L. In Kłodawskie Lake, TDS values ranged from 309 to 388 mg/L.

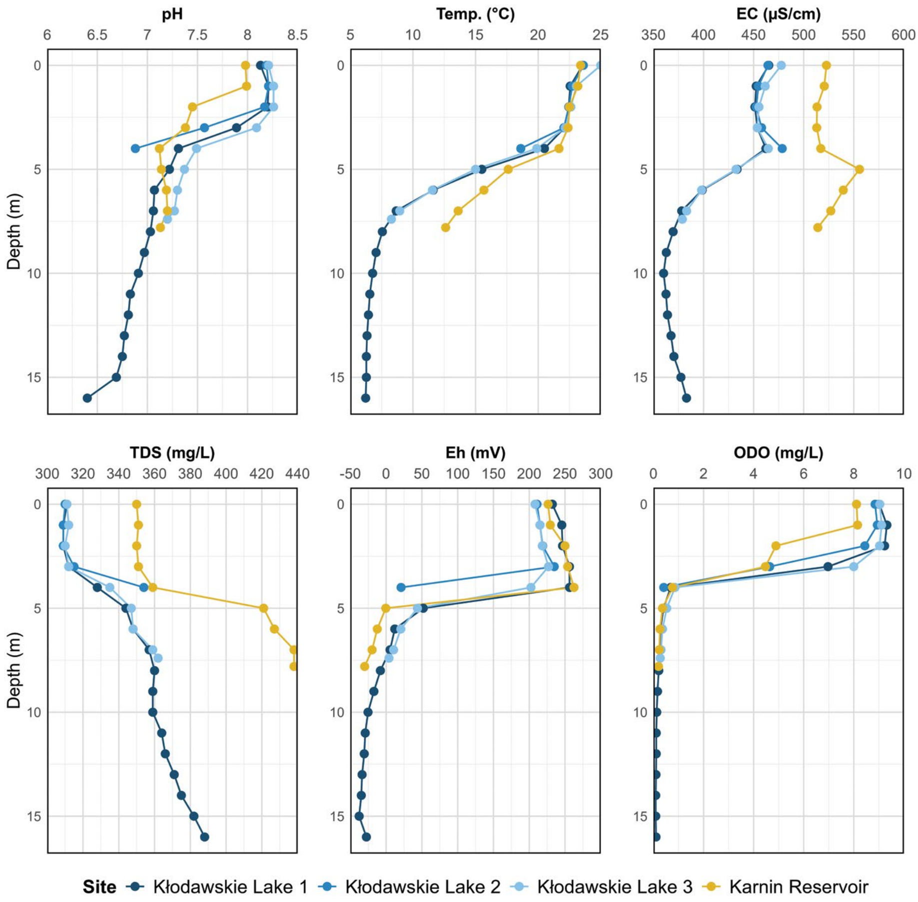

Fig. 2. Basic physico-chemical parameters of the water in Kłodawskie Lake and the Karnin Reservoir

Heavy metals content in water and bottom sediments

The conducted investigations indicate that the highest concentrations of most HMs were recorded at the deepest site of Kłodawskie Lake, namely Site 1. At this location, Cd and Cr showed an increasing trend with depth, whereas Cu, Ni, Pb, and Zn reached their lowest concentrations at 5 m and their highest concentrations at 16 m (Fig. 3A). At 16 m depth (Site 1), HM concentrations were 0.029 µg/L for Cd, 0.37 µg/L for Cr, 5.07 µg/L for Cu, 2.69 µg/L for Ni, 3.05 µg/L for Pb, and 14.5 µg/L for Zn. At the remaining two sites in Kłodawskie Lake, HM concentrations in water were generally comparable to those observed in Karnin Reservoir. At Site 2 of Kłodawskie Lake, the lowest Pb concentrations were recorded relative to the other sites within this lake, whereas at Site 3, elevated Cd concentrations were observed near the bottom, reaching 0.080 µg/L, which was the highest value among all analyzed samples. Karnin Reservoir was characterized by slightly higher Cu concentrations compared to Sites 2 and 3 of Kłodawskie Lake, as well as marginally higher or comparable Cr concentrations (Fig. 3A). Additionally, Karnin Reservoir exhibited the lowest Cd concentrations, ranging from 0.012 to 0.017 µg/L, with uniform values below 5 m depth. However, considering mean values, Karnin Reservoir generally displayed lower HM concentrations than Kłodawskie Lake. Based on average concentrations, the HMs can be ranked in descending order as follows: Zn > Cu > Ni > Pb > Cr > Cd.

Bottom sediments in Kłodawskie Lake exhibited greater homogeneity than the corresponding water samples within the same lake. In contrast, the differences between Kłodawskie Lake and Karnin Reservoir were more pronounced in sediments than in water (Fig. 3B). In Kłodawskie Lake, HM concentrations in sediments can be ranked in descending order as: Zn > Pb > Cu > Ni > Cr > Cd. The maximum concentrations reached 58.8 mg/kg for Zn, 21.2 mg/kg for Pb, 5.88 mg/kg for Cu, 3.06 mg/kg for Ni, 2.75 mg/kg for Cr, and 0.26 mg/kg for Cd. In contrast, in Karnin Reservoir, Cr was the dominant HM, with a concentration of 0.24 mg/kg, while Cd concentrations were below the limit of quantification (LOQ = 0.01 mg/kg), and therefore were not included in further calculations.

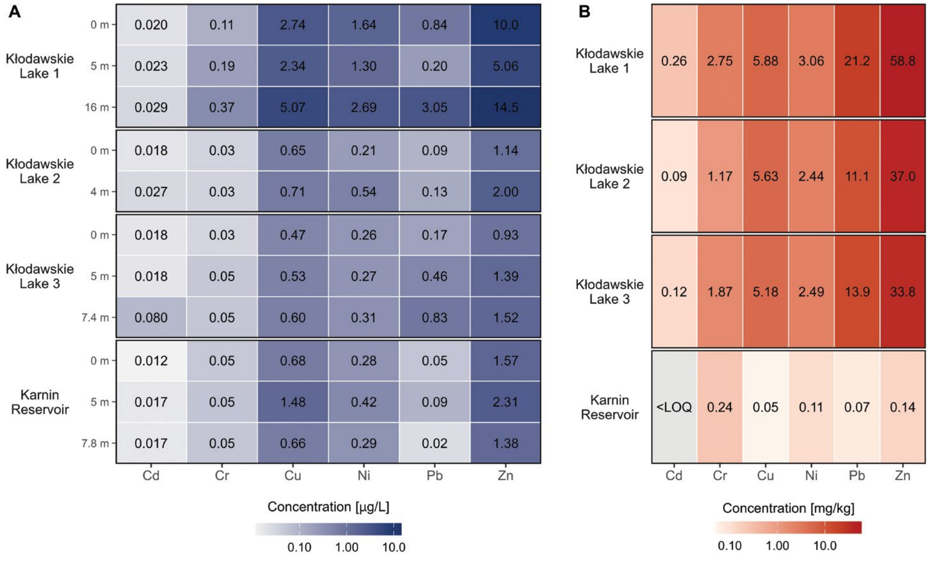

Fig. 3. Concentrations of heavy metals (HMs) in (A) water and (B) bottom sediments of the lakes studied

Heavy metal toxicity in water

The conducted non-carcinogenic risk assessment for HMs in the waters of the analyzed lakes indicates that Cr and Cd contributed the most to the potential risk. The highest HQ value for Cr was recorded at Site 1 in Kłodawskie Lake and reached 1.19×10^{-2} (Fig. 4A). In contrast, the highest HQ value for Cd was found at Site 3 in Kłodawskie Lake, where it reached 3.88×10^{-3}. Pb and Zn ranked next in terms of potential non-carcinogenic risk, whereas the lowest HQ values were clearly recorded for Ni. The highest value recorded in Karnin Reservoir was observed for Cr and amounted to 1.77×10^{-3}.

The analysis based on the HI indicates that no significant cumulative non-carcinogenic risk from all analyzed HMs was identified at any site. The maximum HI value, 1.56×10^{-2}

at Site 1 of Kłodawskie Lake, was substantially lower than the threshold value of 1. Therefore, the possibility of adverse health effects resulting from prolonged dermal exposure to the waters of the analyzed lakes can be excluded.

The carcinogenic risk assessment related to dermal contact during recreational bathing indicated no significant risk for either individual HMs or their cumulative effects (Fig. 4B). The highest ILCR value was recorded for Cr at Site 1 in Kłodawskie Lake, reaching 8.26×10^{-7}, whereas the lowest value was found for Pb at in Karnin Reservoir, amounting to 2.09×10^{-11}. The ∑ILCR values ranged from 6.74×10^{-8} at Site 3 in Kłodawskie Lake to 8.28×10^{-7} at Site 1 in Kłodawskie Lake.

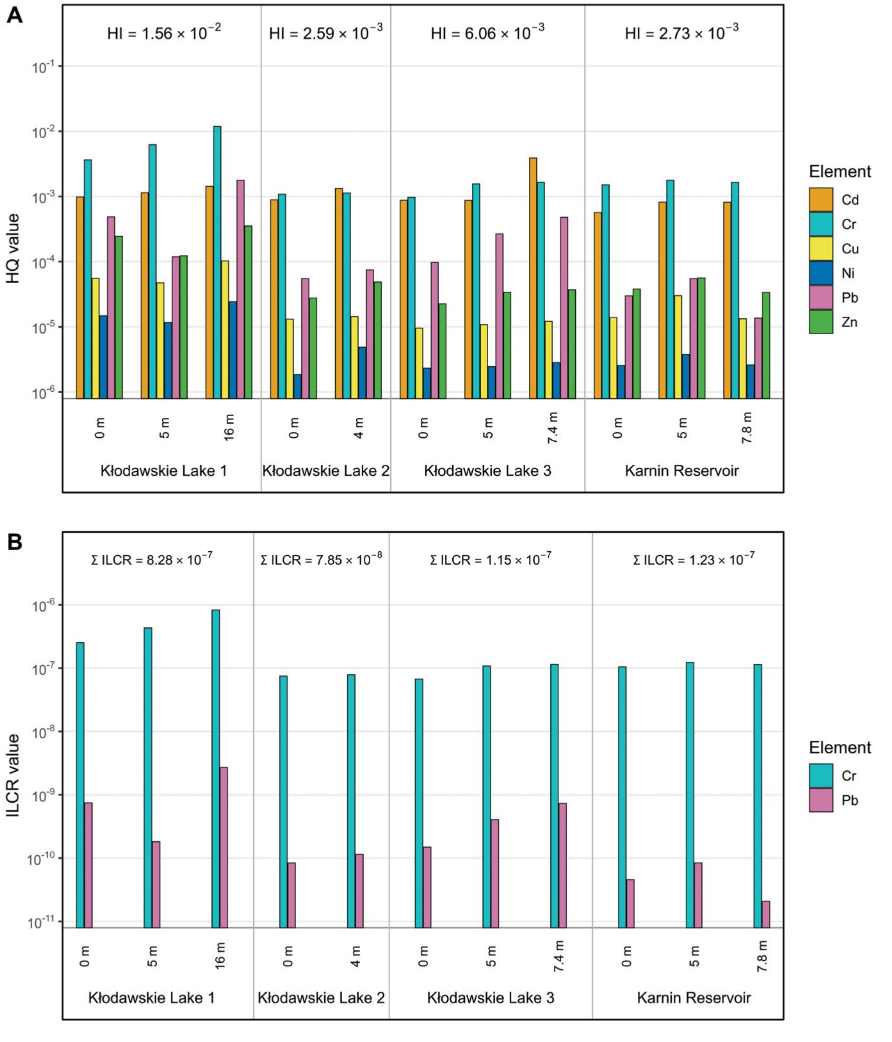

Fig. 4. The values obtained for the potential non-cancer health risk (A) and cancer health risk (B) in the waters of Kłodawskie Lake and the Karnin Reservoir, where the HI and ∑ILCR values listed represent the maximum value recorded at the respective sampling site

The analysis using the integrated index HMTL enabled a quantitative assessment of the potential risks associated with the presence of HMs in water. Consistent with the non-carcinogenic risk assessment, HMTL indicates no toxicity of HMs in the waters of the analyzed lakes and highlights that the highest values were recorded at Site 1 of Kłodawskie Lake (Fig. 5). The maximum HMTL value reached 25 in Kłodawskie Lake and 4 in Karnin Reservoir.

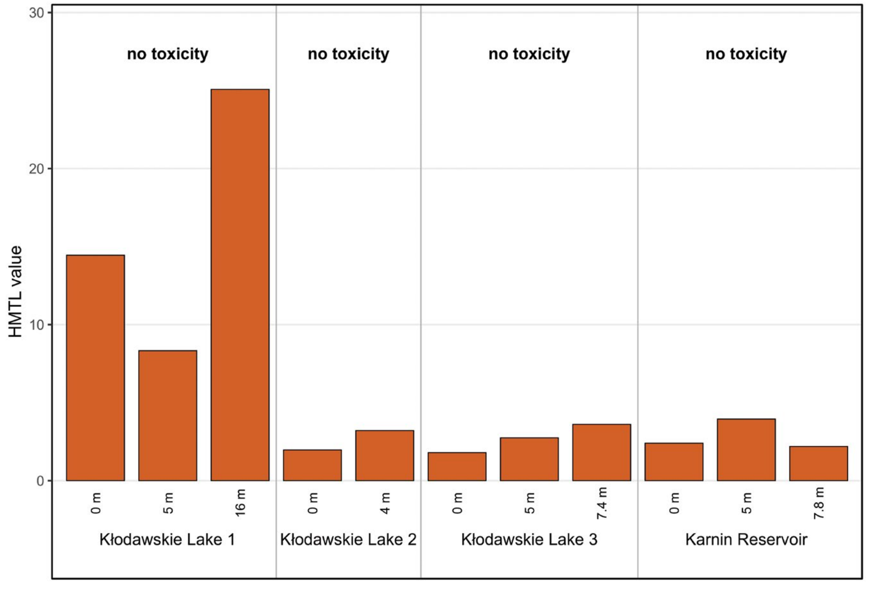

Fig. 5. The values obtained for the heavy metal toxicity load (HMTL)

Heavy metal toxicity in bottom sediments

The analysis of potential toxicity to aquatic biota for individual HMs in water indicates substantial differences between Kłodawskie Lake and Karnin Reservoir, where mHQ did not exceed the very low toxicity threshold at any sampling site, indicating no significant toxicity (Fig. 6). For Cu, very low toxicity was observed only at Site 1 in Kłodawskie Lake. The highest mHQ values were recorded for Pb and Zn, which showed very low toxicity at all sampling sites in Kłodawskie Lake, reaching maximum values of 0.96 for Pb and 0.86 for Zn, respectively. Additionally, at Site 1 and 3 in Kłodawskie Lake, exceedance of the very low toxicity threshold was observed for Cd. At no sampling site did mHQ indicate potential toxic risk associated with Cr.

Integrated indices of HM toxicity, in contrast to mHQ calculated for individual HMs, do not indicate significant toxicological risk related to the presence of HMs in bottom sediments. The calculated mERMQ indicates a probability of toxic effects on aquatic biota below 9% associated with HM occurrence in bottom sediments (Fig. 7A). Only at Site 1 in Kłodawskie Lake do the values approach the first toxicity threshold for mERMQ. TRI values also indicate no toxic risk and remain well below the low toxic risk threshold of 5 for both Kłodawskie Lake and Karnin Reservoir. Maximum values of the integrated indices reached 0.09 for mERMQ and 1.26 for TRI at Site 1 in Kłodawskie Lake, whereas the lowest values were 0.001 for mERMQ and 0.01 for TRI in Karnin Reservoir, clearly highlighting the difference between the studied lakes.

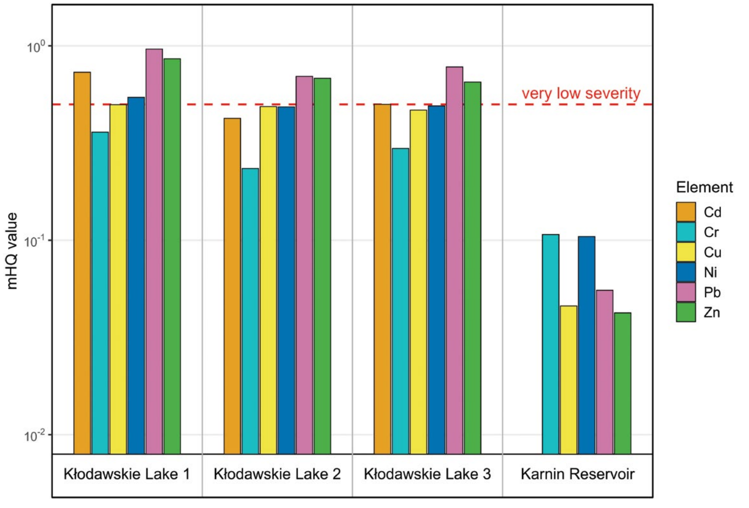

Fig. 6. Toxicity values obtained for individual heavy metals (HMs) in bottom sediments using the modified hazard quotient (mHQ)

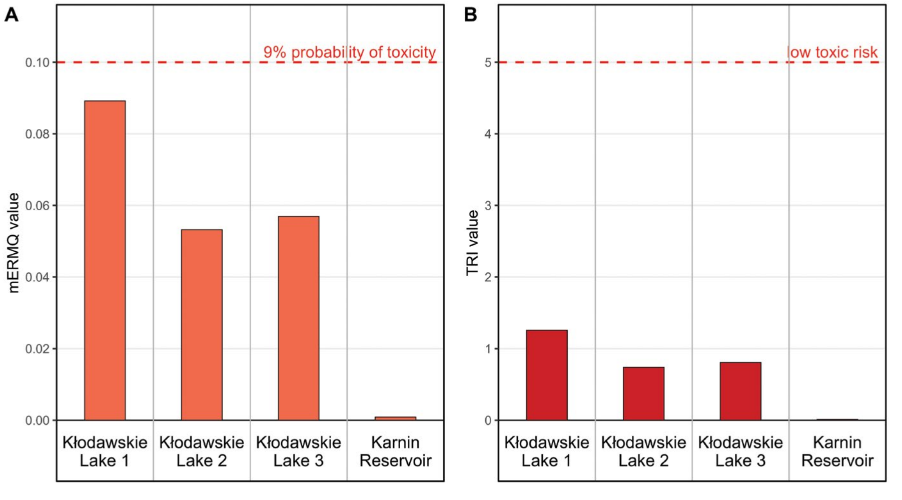

Fig. 7. The values obtained for the integrated assessment of the toxicity of HMs in bottom sediments using the mean effects range-median quotient (mERMQ) and the toxic risk index (TRI)

Discussion

The growing interest in lake tourism in Poland has led to an increasing number of studies addressing research topics that have so far been relatively rarely explored (e.g., Skowron, 2023; Marciniak, 2024; Cichoń & Koczura, 2025). The present study enabled an effective assessment of potential toxicity for humans and aquatic biota, based on a case study of a natural lake and a gravel pit lake. The conducted research indicates that both lakes exhibit similar physico-chemical parameters, including the presence of well-developed thermal stratification (Fig. 2). Concentrations of HMs in the waters of both lakes were generally comparable, with the exception of the deepest site in Kłodawskie Lake, where elevated values were recorded (Site 1). The highest concentrations of HMs were generally observed near the bottom of the studied lakes (Fig. 3A), which is directly related to the occurrence of stratification leading to anoxic and reducing conditions in the hypolimnion, potentially resulting in the remobilization of HMs from bottom sediments or their persistence in the water column (Linnik et al., 2023).

The analysis of potential non-carcinogenic and carcinogenic risk associated with HMs present in water indicates no significant health risk related to dermal exposure (Fig. 4). Additionally, the analysis based on HMTL suggests that, from a quantitative perspective, there is no potential toxic risk for humans (Fig. 5). As indicated by the World Health Organization (2021), there are no simple, universally applicable guidelines for determining threshold concentrations of chemical contaminants in recreational waters that would account for varying exposure frequencies and intensities. In the present study, both a quantitative approach and long-term dermal exposure were considered, which suggests that the recreational use of the studied lakes is unlikely to pose a significant health risk for tourists. Furthermore, the concentrations of HMs in the studied waters are well below the recreational water screening values established by the World Health Organization (2021). Nevertheless, these screening values may serve as a useful reference for identifying other lakes in Poland that are intensively used for recreational purposes and where similar analyses should be conducted, particularly in areas characterized by strong anthropogenic pressure and/or complex geochemical conditions, such as the Upper Silesian Anthropogenic Lake District (Rzętała & Jaguś, 2012).

Concentrations of HMs in the bottom sediments of the studied lakes exhibited considerably greater variability than in the water (Fig. 3B). HM concentrations in the bottom sediments of Kłodawskie Lake were significantly higher than those in the Karnin Reservoir, which may be related to the long-term human use of the lake (Gaziński, 2003), as well as the generally higher organic matter content in sediments of natural lakes, enhancing the binding of HMs to bottom sediments (Sojka et al., 2019a, 2024; Śniady et al., 2026). As indicated in previous studies, gravel pit lakes are generally characterized by lower concentrations of nutrients (Søndergaard et al., 2018; Vucic et al., 2019), and their chemical composition may strongly depend on the surrounding land use (Mollema & Antonellini, 2016). Therefore, in the absence of significant HM inputs resulting from land development, as well as in the absence of substantial HM-bearing minerals in the geological substrate (e.g., sulfides such as chalcopyrite and galena), gravel pit lakes are typically characterized by low HM concentrations (Mollema & Antonellini, 2016). Additionally, a positive aspect of pit lakes formed in Quaternary sandy-gravel deposits is their tendency to maintain slightly alkaline pH conditions (Marszelewski et al., 2017), which may promote the adsorption and co-precipitation of HMs with Fe and Mn (oxyhydr)oxides in bottom sediments, leading to their immobilization (Mollema & Antonellini, 2016; Śniady et al., 2025).

The conducted study indicates that, considering the cumulative impact of all HMs, no significant toxic effects on aquatic biota are expected (Fig. 7). However, a clear difference is observed between the Karnin Reservoir and Kłodawskie Lake, where HM concentrations are considerably higher. This is reflected in the mHQ used for the individual assessment of potential toxicity of specific HMs, which indicates initial very low toxicity for Pb and Zn, and to a lesser extent for Cd, Cu, and Ni (Fig. 6). Generally, despite the lack of significant toxic risk, the observed differences between the studied lakes suggest that natural lakes, such as Kłodawskie Lake, may act as long-term sinks for HMs (Algül & Beyhan, 2020), whereas in the Karnin Reservoir they have not yet accumulated to the same extent.

It should be additionally emphasized that, within the bathing season in Poland, which usually lasts from late May to the second half of September (Skowron, 2023), temporal variability in the input of HMs to lakes and in their mobility may occur, related, among other factors, to changes in the physico-chemical parameters of water (Linnik et al., 2023). Spatial variability in HM distribution may also be important, particularly in flow-through lakes, where hydrological conditions may promote differences in their distribution within the lake basin (e.g., Kuriata-Potasznik et al., 2016, 2018; Sojka et al., 2018). This should be taken into account when planning studies in lakes with different hydrological regimes, as well as in large lakes where spatial heterogeneity may be more pronounced (Kostka & Leśniak, 2020). In the present study, samples were collected in the middle part of the bathing season and from a limited number of sites, adjusted to the characteristics of the studied lakes; therefore, the obtained results should be treated as screening-level values. In the future, however, it would be advisable to conduct studies covering the entire bathing season, which would allow the potential variability in HM concentrations and mobility to be better recognized, resulting from both natural changes in environmental conditions and variable anthropogenic pressure.

In a broader context, despite the relatively low HM toxicity indicated by the present study, it should be noted that, in addition to chemical pollutants, microbiological contamination, particularly bacteria of the Coli group, plays an important role in the context of recreational water use (Cichoń & Koczura, 2025). Moreover, the recreational use of lakes involves a range of activities that contribute to increased anthropogenic pressure on lake ecosystems (Sun & Liu, 2020; Pásková et al., 2024). Among these, activities related to the use of motorized watercraft are particularly significant, as they may lead not only to pollutant emissions but also to biological disturbances (e.g., reduced spawning success and feeding efficiency of fish) and physical impacts (e.g., shoreline erosion, increased water turbidity, and damage to aquatic flora and fauna) (Mosisch & Arthington, 1998; Cichocki, 2025). Therefore, efforts should be made, on the one hand, to identify lakes with potentially hazardous concentrations of HMs where similar analyses should be conducted, and on the other hand, to extend such analyses to include other forms of anthropogenic pressure in order to achieve a more holistic assessment of the impacts of tourism on lake ecosystems. Additionally, the conducted study highlights the potential of gravel pit lakes as important sites for tourism development in Poland, which may be particularly relevant in regions characterized by a low number of natural lakes.

Conclusion

The conducted study, involving the analysis of HM concentrations and their potential toxicity in the waters and bottom sediments of two lakes of different origin in the vicinity of Gorzów Wielkopolski, allowed for the formulation of the following conclusions:

1. HM concentrations in water are comparable between Kłodawskie Lake and the Karnin Reservoir and can be arranged in decreasing order based on mean values as follows: Zn > Cu > Ni > Pb > Cr > Cd. In contrast, clear differences are observed in bottom sediments, where significantly lower concentrations were recorded in the gravel Karnin Reservoir.
2. The analysis of potential non-carcinogenic and carcinogenic risk associated with dermal exposure indicates no significant health risk for humans during regular use of both lakes. These results were confirmed by the analysis using the heavy metal toxicity load (HMTL), which enabled a quantitative assessment of potential risk.
3. The assessment of potential toxic risk for aquatic biota, conducted using integrated indices, indicates no significant risk. At the same time, the analysis of individual HMs using the modified hazard quotient (mHQ) revealed very low toxicity for Pb and Zn, and to a lesser extent for Cd, Cu, and Ni in Kłodawskie Lake, whereas no significant contamination was identified in the Karnin Reservoir.
4. The results obtained constitute an example of a toxicological assessment of lakes used for recreational purposes and may serve as a basis for the development of similar analyses in water bodies subjected to strong anthropogenic pressure.
5. The conducted study highlights the potential of gravel pit lakes in the context of tourism use. Under favorable geochemical conditions, they may constitute an important alternative to natural lakes, particularly in regions characterized by a low number of natural lakes.

Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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