Toxicity studies on sediments near hydropower plants on the Ślęza and Bystrzyca rivers, Poland, to establish their potential for use for soil enrichment

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Abstract
The aim of this study is to analyze the toxicity of the sediments accumulated in the vicinity of hydropower plants (HPs) on the Ślęza and Bystrzyca rivers in Poland and the possibility of using these sediments for soil enrichment purposes. Thus far, there has been little comprehensive research related to the analysis of the impact of HPs on the properties of sediments. The analysis of the granulometric composition, physicochemical properties, heavy metals (HMs) content in sediments, and the growth of three plant species was carried out, including toxicity (HMs) and germination indices (plants). Most parameters were significant between the points upstream and downstream of the analyzed HPs. It has been shown that the most dangerous toxic factor is the high concentrations of Cu, Ni, and Zn in the sediments upstream of the HP on the Ślęza. In most cases, the HMs content was observed to decrease downstream of the HPs (e.g., Cu in Ślęza River: average of 13.44-times), a result of changes in the particle size composition and accumulation of sediments at the site of the dam wall. Typically, the sediments tested stimulated growth in the plant species studied in comparison with the control groups (e.g., germination index for Sorghum saccharatum, Bystrzyca: 273.5% downstream of HPs). The C:N ratio increased downstream of the HPs by an average of 37.11% for the Ślęza River and 10.88% for the Bystrzyca River. The requirements for composting material were not met; however, the sediment could be used to enrich soils with an excessively wide C:N ratio.

KEYWORDS
etcotoxicology, heavy metals, hydropower plants, rivers, soil enrichment, surface sediment quality

1 | INTRODUCTION

The operation of hydropower plants (HPs) situated on rivers affects the properties of bottom sediments (Kuriqi et al., 2021; Tomczyk & Wiatkowski, 2020). This is due to turbulence zones forming downstream from the dams, which results in increased erosion (J.-H. Wu & Ma, 2018). Impoundment also results in the accumulation of sediments (Wiatkowski & Tomczyk, 2018). Therefore, a clear differentiation of the grain size composition within these hydrotechnical facilities can be observed: materials with larger particle diameters (e.g., stones and gravel)
dominate upstream, while downstream, materials with smaller particles predominate (e.g., sand and silt) (Bogen & Bønsnes, 2001). As the particles move away from the HPs, the particle size in the bottom sediments decreases, that is, stones are present in the immediate vicinity of the HPs, then gravel and sand, and further down, silt and clays (Bishkawakarma & State, 2010; López et al., 2020).

Previous studies have shown that, downstream of HPs, there is an increase in the concentration of heavy metals (especially Zn, Al, Co, Ti, and Fe) (Bai et al., 2009). This is due to changes in the saturation of bottom sediment minerals and suspended material (klaver et al., 2007; Song et al., 2010). Moreover, because of the decomposition of organic matter present in sediments, the greenhouse gases released contribute to global warming (Agrawal & Sharma, 2012; Barros et al., 2011; Gagnon & van de Vate, 1997; Soininen et al., 2019).

The sediment composition is also modified by land use in the adjacent catchment area (Haddadchi & Hicks, 2019), especially when this is arable land (causing surface runoff of fertilizers and plant protection products rich in nutrients; Ferreira et al., 2020; Lee & Oh, 2018), as well as industrial sites (Hayzoun et al., 2014), landfills (Zinabu et al., 2019), and sewage treatment plants (sources of specific organic pollutants as well as heavy metals) (Loizeau et al., 2004; B. Wu et al., 2014). Water and sewage management in the catchment area (Wiatkowski, 2015) and potential waste discharge into rivers are also of primary concern (Jordão et al., 2002).

Various substances, including heavy metals, are present in the bottom sediments. They originate primarily from rock formations extruded from the Earth’s core, but due to the by-products of industrial and agricultural activities, their quantities are constantly increasing (Amin et al., 2009; Chapman et al., 2005). At appropriate concentrations, they are necessary for the functioning of living organisms, occurring in various environments (e.g., they are a building component of cells) (Volland et al., 2014), however, in large quantities, they can be highly toxic, and affect living organisms in their vicinity (due to their long-term accumulation in tissues (Al-Reasi et al., 2007; Pokorny et al., 2015). This is because they do not biodegrade (dra et al., 2019; Kasperek et al., 2013). For example, excess Cd disrupts nutrient absorption by plants (Jaishankar et al., 2014), while Pb causes kidney and brain damage (Z. Rahman & Myronidis, 2011). Our study highlights the possibilities of sustainability in each of these aspects. Thus far, there has been little comprehensive research related to the analysis of the impact of HPs on the properties of bottom sediments; research has mostly been on the physicochemical aspects. We have used an interdisciplinary approach to also study the sedimentological and ecotoxicological aspects. A novelty in this study is the temporal and spatial study of the toxicity of bottom sediments to selected species of crops grown near HPs, together with the assessment of the possibility of their use for soil enrichment, which has not been done so far for this type of hydrotechnical structures.

2 | MATERIALS AND METHODS

2.1 | Sample collection

HPs located on two rivers in Poland (blocking the entire cross-sections of their channels), the Bystrzyca and the Ślęza rivers were chosen for the research (Figure 1). Samples were taken in April and October 2019, at a distance of 150 m upstream and downstream of the hydrotechnical structures, every 20 or 25 m (20, 40, 60, 80, 100, 125, and 150 m) (HP on the Bystrzyca: 51°03′17″N 16°47′48″E; Ślęza: 51°08′33″N 16°56′54″E) and at reference points (Bystrzyca: 51°03′29″N 16°47′50″E and 51°04′38″3′N 16°49′04″E; Ślęza: 51°00′11″N 17°00′34″E). A 2500 cm² Van Veen bottom sediment sampler was utilized for the sampling. At each location, at least 1 L of the top layer of the hydrated sediment (approximately 3 cm thick) was collected. The samples were deposited into polyethylene bags, marked with an appropriate label, and then transported to the laboratory in a refrigerator (Duodu et al., 2016).

2.2 | Sample preparation and analysis

Before analysis, the samples were stored at a temperature of approximately 20°C. After the samples were placed in a fume hood and air-
dried, they were marked according to particle size distribution using the Bouyoucos areometric method as modified by Casagrande and Prószyński, and dividing the samples into appropriate divisions using sieves of varying mesh size (Błażejczak et al., 2020; Waroszewski et al., 2019). They were also divided according to heavy metals (HMs) content (mineralization in aqua regia and determination by atomic absorption spectrophotometry) (He et al., 2016; Sarmani, 1989), EC (with a conductometer), and pH (potentiometric method in water). Depending on the method used, the measurement error ranged from 0.5% to 5% (EC—0.5%, pH, C:N—2.0%, other parameters—5.0%).

Grain size classification was established based on the classification according to the Polish Soil Science Society of 2008 (PSSS, 2008). The following divisions with the assigned particle diameters were discovered: rock fragments >2 mm were boulders, stones, or pebbles; fine earth particles <2 mm were sand (fraction of 2–0.05 mm), silt (fraction of 0.05–0.002 mm), or clay (fraction of <0.002 mm). Depending on the percentage of non-organic matter present, specific groups and granulometric subgroups can be distinguished (Bieganowski et al., 2013; Kruczkowska et al., 2020).

Toxicity tests were performed on the seeds of three species of crops, that is, white mustard (SA), garden cress (LS), and bicolor sorghum (SS), using the Phytotoxkit™ acute toxicity microbiotest (compliant with ISO 18763). To observe the determinations, 10 seeds of each species were planted in the previously prepared sediment (with 100% humidity). Each sediment sample was placed in a transparent container, which made it possible to observe seed germination, as well as measuring the length of the roots and shoots after 3 days of growth (the samples were kept in complete darkness at room temperature). In addition, the reference soils were analyzed to determine the potential toxicity of the sediment samples within HPs. All experiments were performed in triplicate. A limitation of the test may be that the plant roots are separated from the sediment by filter paper, which may have some influence on the results; such factor may also be slightly different conditions of seed incubation in particular test dates (e.g., air temperature, humidity, and light intensity).

### 2.3 Data analysis

The resulting data was further analyzed as follows:

1. Determination of basic statistics for the studied parameters in individual rivers (minimum, maximum, median, mean, and SD) along with plotting box plots; wherever possible, synthetic indicators were adopted to show the variability of the tested parameters (granulometric composition—average grain diameter \( D_{50} \), calculated as a weighted average from the obtained results); physicochemistry (pH, EC, C:N ratio); heavy metals (Cu, Ni, Cr, Zn, Pb, and Cd); action on plants [germination index (GI) for SA, LS, and SS]. This point was discussed in Supplementary material (Appendix...
2. Calculation of toxicity indices for HMs: geochemical method (Piernowta et al., 2020), LAWA (Tomczyk et al., 2021), pollution Factor (P) (Kowalska et al., 2018), Nemerow index (IN) (Z. Li et al., 2019), geoaccumulation index (Igeo) (Kilunga et al., 2017; Santos-Francés et al., 2017), contamination factor (C) (Sollig & Parmah, 2015), ecological risk index (E) (M. S. Rahman et al., 2014; Hakanson, 1980), classification for each sample in the LAWA and geochemical methods (Table A1 in Appendix A), or calculations (other parameters; Table A2); final classification in Table A3.

3. Determination of the toxicity index for the three tested plant species (SA, LS, and SS) according to the GI, calculated from the formula (1):

\[ GI = \frac{L_s \cdot G_s}{L_0 \cdot G_0} \times 100\% \]  

Where: \( L_s \) is the root length increase in the tested sample (number of seeds in the sample \( n = 10 \); mm), \( G_s \) is the percentage of germinated seeds in the sample, \( L_0 \) is the increase in root length in the blank sample (\( n = 3 \); mm), and \( G_0 \) is the percentage of germinated seeds in the blank sample (García-Lorenzo et al., 2014; GI < 90%, inhibitory effect; GI = 90%–110%, no effect/non-toxic; and GI > 110%, growth stimulating effect (Baran & Tarnawski, 2013; Czerniawska-Kusza & Kusza, 2011).

4. Determining the significance of the obtained results by comparing the results upstream and downstream of the HPs using the non-parametric two-sided Mann–Whitney U test (Wilcoxon rank test). As the null hypothesis, it was assumed that the medians for the analyzed samples are identical, and the distribution of the dependent variables does not coincide with the normal distribution (for \( p < 0.05 \) or \( p < 0.01 \)); in the test, \( U \) and \( z \) values are calculated using the Formulas 2 and 3:

\[ U = \frac{n(n + 1)}{2} - \sum \text{ranks} \]  

Where: \( n \) is the number of items in the samples and \( \sum \text{ranks} \) is the sum of ranks in the sample.

\[ z = \frac{U - \mu_U}{\sigma_U} \]  

Where: \( \sigma_U \) is the SD of \( U \) and \( \mu_U \) is the mean of \( U \).

5. Estimating the relationship between all examined parameters for both rivers using the Spearman’s rank correlation coefficient (for \( p < 0.05 \) [Leeb et al., 2015]; selection due to data distribution other than normal), principal component analysis (PCA) and hierarchical cluster analysis (HCA). As part of the PCA, the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy, the Bartlett’s test of sphericity and communalities were determined, which allowed for further analysis.

The following software was used for the analyses: SPSS Statistics 26, ORIGIN Pro 2021b, STATISTICA 13, Microsoft Office 2013, and QGIS 2.8.4.

The procedure for assessing the suitability of bottom sediment for agricultural use is presented in Figure A1, whereas conditions for the accumulation of sediment in a natural river and after the construction of a HP—in Figure A2 (Appendix A).

3 | RESULTS

3.1 | Toxicity indices for heavy metals

Table C1 (Appendix C) shows the results of the seven calculated HMs indices. In most cases, at points downstream from the HPs on the Ślęza and Bystrzyca rivers, the toxicity indices showed more favourable values than upstream (exceptions: Cu–IN; Pb geochemical method, Ślęza; Cd–IN, Ślęza). At reference sites, these values were usually more favourable or average (exceptions: Cr for four methods, Ślęza; Pb for six methods, Bystrzyca).

In the case of the geochemical method, the highest pollution was recorded for Cu and Ni upstream of the HP on the Ślęza River (class IV, noticeable pollution), as well as for Cr, Zn, Cd, Cu, Ni, and Cr in the equivalent sample sites in the Bystrzyca River (class III, average pollution). In the remaining cases, negligible or low pollution levels (class I or II) were observed. The most favourable results were recorded for Pb (class I everywhere, except for points downstream of the HP in Ślęza, class II), where the concentrations of this element did not exceed, or differed slightly, from the geochemical background adopted for Poland.

For the LAWA method, results ranging from class I to class III were recorded. Class III was recorded for Cu (upstream and downstream of the HP on the Ślęza River, NI, and Cd (in both cases at points upstream of the HP on the Ślęza River). The pollution levels were moderate and indicate a moderate impact of anthropopressure on the quality of sediments. The best quality was noted for Cr class I everywhere, and for Pb, in most cases there was no pollution caused by this element, only upstream from the hydrotechnical structure on the Ślęza River where the pollution levels were low.

The \( P \), indicating that the pollutant standards of the analyzed elements were met, showed mostly negligible or slight contamination at the sites tested. The only exceptions were the results achieved at points upstream from the Ślęza HP for Zn (class IV, noticeable pollution), Cu and Ni (average pollution).

The results for the IN indicate a noticeable contamination of Cu downstream of the HP on the Ślęza River, as well as Ni and Zn pollution upstream (class IV). A class III level of cleanliness was discovered for Cu upstream of this hydrotechnical structure. In the remaining cases, negligible or slight contamination was noted (the lowest was for Cr and Pb class I).
For the Igeo, similar relationships were observed as discovered from the IN upstream of the HP on the Ślęza River, that is, noticeable for Cu and Ni pollution (class IV), and average for Zn and Cr (class III; in the case of Cr also in the reference point). In other cases, no significant increases were seen (class I or II). For Cd, no deviations from the adopted standards were observed.

The C1 is important because it considers the toxicity of heavy metals. The calculations show that the sediments upstream of the HP on the Ślęza River showed the greatest toxicity (Cu and Ni—class V, Cr and Zn—class IV, Pb—class III, and Cd—class II). Upstream of the HP on the Bystrzyca River, observations were Cu, Ni, and Cr—class IV, Zn—class III, Pb and Cd—class II and at the reference points on the Bystrzyca River (Cu, Ni and Cr—class III, Zn, Pb and Cd—class II). Class IV levels were recorded for Cr at the reference sites on the Ślęza River, and class III downstream from the HP. The most favourable values (class I or II) were observed downstream of the HP on the Bystrzyca River.

Regarding the Eh, an average risk of pollution (class III) was recorded for Cu and Cd upstream of the HP on the Ślęza River. A lower risk (class II) was observed for Ni upstream of the HP and for Cd at the reference points, and upstream of the HP on the Bystrzyca River. In other cases, there was no risk of contamination (class I), which was the lowest value found for Cr, Zn, and Pb.

The calculated indices of the toxicity of heavy metals indicate that the most problematic element that has the greatest impact on the environment was Cu upstream of the HP on the Ślęza River. It exceeds the adopted limit values and exhibits high concentrations which qualify the sediments containing it for remediation (the average class of the calculated indicators is 3.57). In the same sample sites, Ni and Zn levels were negatively represented (average 3.29 and 3.00). In other cases, these values fluctuate in the range corresponding to class I or II of sediment purity (averaging 1.00–2.43). Considering all the average values for the calculated indices of HMs, the cleanest to the most polluted sample sites can be arranged as follows: Bystrzyca downstream < Ślęza reference < Bystrzyca reference < Ślęza downstream < Bystrzyca upstream < Ślęza upstream (respectively: 1.14 < 1.19 < 1.36 < 1.40 < 1.76 < 2.60). Using the classification according to the point scale for the geochemical and LAWa methods, all points except Ślęza upstream can be classified as class I, with Ślęza upstream being class III.

3.2 | Germination index

Many authors emphasize the fact that biotests are a good addition to the chemical analyses used for the qualitative classification of sediments (Mamindy-Pajany et al., 2011; van der Vliet et al., 2012). They are well known but rarely used in practice, even though they are very important from the point of view of organisms living in the environment (Hassan et al., 2016; Szymańska-Pulkowska & Wódowy, 2021). Therefore, in addition to physicochemical analyses, toxicity tests were carried out to evaluate the sediments.

The research was conducted on two species of dicotyledons (SA and LS) and a monocotyledonous plant (SS).

Figure 2 shows the assessment of the phytotoxicity of bottom sediments using the general GI, which takes into consideration seed germination and root length.

The plants reacted differently to contaminants in the bottom sediments. The GI value of the sediments ranged from 1% to 780% for LS, 35% to 190% for SA, and 112% to 469% for SS.

LS was the most sensitive to pollution in the sediment, but at the same time it had the highest GI index. In this study, the lowest GI index in each of the analyzed variants (i.e., downstream, upstream of the HP, and at the sampling sites) was maintained for the SA species.

SS plants showed the lowest sensitivity to the potential phytotoxicity of the sediment samples. Bottom sediments from all components analyzed for this species showed a growth stimulating effect.

The value of the GI index varied depending on the location of the sample points on the river (downstream, upstream of the HP, and at reference sites) and between two selected objects (Ślęza, Bystrzyca). Visible differences were also noted between the three plants selected for study, therefore the selection of appropriate species is a very important issue, as they should be able to survive the potentially toxic effects of the sediment and its variability over time (Madera-Parra et al., 2015).

In most cases, the sediment showed a growth stimulating effect caused by a large quantity of nutrients in comparison to the control sample. Despite the increased content of Cu and Ni observed in the sediments, their toxic effects on the plants were not demonstrated, which is explained by the ability of trace elements to combine with organic matter. As a result, the chance of them being released from the sediment is much lower, making them less toxic (Baran et al., 2019). There were no major changes in the GI index between the points located upstream and downstream of the HP. In the case of the Ślęza River, both dicotyledonous plants (SA and LS) showed a higher GI index upstream of the HP.

Figure 3 shows the assessment of the phytotoxicity of bottom sediments using the GI, and accounts for the different seasons in which toxicity studies were conducted.

To account for seasonal changes, sediment toxicity analyses were carried out in two separate seasons, that is, spring and autumn.

It was observed that the sediment collected in spring had a more growth stimulating effect on plants than that collected in autumn. The GI index for sediment collected in spring was up to 469% for Bystrzyca and 780% for Ślęza. However, in autumn, it was lower, in the range of up to 315% for the sediments from Bystrzyca and 413% for the sediments from Ślęza. However, in two cases, a higher growth stimulating effect of the sediment collected in autumn than in spring was noted, (i.e., for LS from Bystrzyca and SS from Ślęza).

Sediment from the two rivers showed a plant growth-stimulating effect in most cases; however, there were also cases where the sediment had no effect or even an inhibitory effect on plant growth. When placed in order, the registered number of toxic responses in
3.3 | Statistical significance test (Mann–Whitney U test)

The statistical analysis performed to compare the medians for groups of points upstream and downstream of the HPs in the Bystrzyca and Ślęza rivers showed statistical significance for most of the parameters tested for \( p < 0.01 \) (exceptions were: GI-SA for the Ślęza River, EC and C:N for the Bystrzyca River—significance for \( p < 0.05 \); GI-LS and GI-SS for the Ślęza River and pH, GI-SA, GI-LS and GI-SS for the Bystrzyca River—no statistical significance). This means that in most cases, HPs affect the analyzed parameters such as heavy metals, grain size composition, EC, and C:N ratio, as indicated by the calculated values of \( U \) and \( z \). For the Ślęza River, the greatest impact was for Cu, Ni, \( D_{50} \), Zn, and EC, while for the Bystrzyca River, it was for Pb and \( D_{50} \) (Table D1; Appendix D).

3.4 | Differences between the studied parameters (PCA, HCA, and correlation matrix)

PCA and HCA indicate the arrangement of parameters into groups, and the correlation matrix on their interactions with the determination of their direction and strength of correlation. The calculations of the KNO measure showed a high adequacy of data sampling (Ślęza: 0.834; Bystrzyca: 0.794), the Bartlett’s test of sphericity confirmed their statistical significance (<0.001), and the communalities analysis made it possible to reject in PCA parameters with values <0.5 after extraction (Ślęza: C:N, GI-SA; Bystrzyca: GI-SA) (Myronidis & Ivanova, 2020). For both rivers, mutual, statistically significant interactions which were directly proportional (\( p \leq 0.05 \)) were found between each of the analyzed HMs (Cu, Ni, Cr, Zn, Pb, and Cd) and EC. At the opposite end of the spectrum, parameters such as \( D_{50} \) and pH vary inversely with heavy metals and EC, but are directly proportional to each other. The interactions between these parameters are statistically significant for both rivers. In the case of C:N and GI for individual

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**FIGURE 2** Germination index values (GI) in sediment samples for: (a) *Sinapis alba*, (b) *Lepidium sativum*, and (c) *Sorghum saccharatum*; where U, upstream of hydropower facility; D, downstream of hydropower facility; and R, reference point; a, statistical significance for the Mann–Whitney U test (* at \( p < 0.05 \)) [Colour figure can be viewed at wileyonlinelibrary.com]
plant species, no specific direction of changes in relation to other parameters was found, and they were not statistically significant (the C:N was statistically significant for most parameters in the Ślęza River, similar to GI-SA and Ni, Cr, Pb, Cd). The HCA, PCA and Spearman correlation matrix results for both rivers are shown in Figures 4 and 5 and in Tables E1–E6 and Figures E1 and E2, Appendix E).

For the Ślęza River, three components with eigenvalues higher than 1.0 were distinguished, describing about 86% of the results, and for the Bystrzyca River, four, characterizing over 87% of the obtained results. For the first component of the Ślęza River, a very strong correlation ($r > 0.9$) was noted for Ni, Zn, Cu, EC, and D$_{50}$, for the second—for GI-SS, and for the third—for GI-LS. In the case of Bystrzyca River, these were respectively: the first component—Zn, Cr, Ni, Cu, and Cd, the others—none. In most cases, the values were strongly correlated in specific components, that is, $r > 0.7$ (exceptions: Ślęza—Cr; Bystrzyca—pH, Pb, GI-LS).

The strength of the correlation varied. Regarding the pairs of statistically significant parameters, a high correlation index (upstream 0.70) was observed in the Ślęza River between most HMs (exceptions: Cr/Cu, Zn/Cr, and Pb/Cr) and EC and heavy metals (except Pb) and pH. For the Bystrzyca River, high correlation indexes were also found between most HMs (exceptions: Pb Ni, Pb/Cr, Pb/Zn, and Pb/Cd), pH/D$_{50}$ and EC, and heavy metals, D$_{50}$, and pH.

4 | DISCUSSION

4.1 | Toxicity indices for heavy metals

The bottom sediments with the higher contents of Cu, Ni, and Zn need to be remediated to improve their composition (R. Zhao et al., 2020) (Figures B5, B6, and B8, Appendix B; Table C1, Appendix C). For this purpose, one of two reclamation strategies is used (Wuana & Okieimen, 2011), that is, immobilization of pollutants in the solid phase such as changing the properties of the sediments, namely their reaction and sorption capacity using various treatments such as...
liming, application of organic additives and silting. However, these methods are not recommended because HMs immobilized in the sorption complex may be released into the environment due to changes caused by reactions (Guo et al., 2017; Hamid et al., 2018; Ou et al., 2018), removal of pollutants from the soil (contaminants migrate from the solid phase to the soil solution; recommended methods such as washing, extraction, electrochemical methods, evaporation of pollutants, phytoremediation) (Leštan et al., 2008; Sharma et al., 2018; Yan et al., 2020) or methods combining both strategies (e.g., the use of synthetic zeolites) (Boros-Lajszner et al., 2017; Cataldo et al., 2021; Szerement et al., 2021). Which application method is applied depends on technological possibilities, financial resources, type of pollution, and soil properties. In the case of Cu, Ni, and Zn, phytoremediation which uses plants that hyperaccumulate these elements in their tissues, producing large biomass in a short time, is recommended (e.g., bioenergy crops: willows and miscanthus). The components of the plants found upstream on land are mowed and then stored or burned (Di Lonardo et al., 2011; Šyc et al., 2012; B. Wu et al., 2021). A

**FIGURE 4** (a–c) Hierarchical cluster analysis, principal component analysis, and Spearman correlation matrix results for parameters tested in the sediments of the Ślęza River (* significant at *p* < 0.05) [Colour figure can be viewed at wileyonlinelibrary.com]
The second method recommended is the use of synthetic zeolites, which are clay materials with high sorption capacity. They are placed in the purified sediment in the form of briquettes which powerful immobilize easily soluble forms of various substances in the sediment and are then easily removed (Belviso, 2020; Kozera-Sucharda et al., 2020; J. Li et al., 2018). The biggest disadvantage of the first method is its varying effectiveness, while the second method has high implementation costs (Wuana & Okieimen, 2011).

### 4.2 Germination index

In Trojanowska's research on the use of Phytotoxkit tests to assess the risk posed by bottom sediments in a dam reservoir, in each of the analyzed cases, the highest phytotoxicity was observed for LS (Trojanowska, 2011).

The lowest GI index maintained for the SA species in this study (Figures 2 and 3) may be due to it being a species that shows a high...
sensitivity to a very wide range of chemicals (Kalčíková et al., 2014; Vaverková et al., 2020; Wdowczyk & Szmyraska-Pulikowska, 2021).

In this study, SS plants showed the lowest sensitivity to the potential phytotoxicity (Figures 2 and 3), while in other studies, SS was classified as the most sensitive species of the three studied (Baran & Tamawski, 2013; Czerniawska-Kusza & Kusza, 2011; Mamindy-Pajany et al., 2011).

Despite the increased content of Cu and Ni observed in the sediments (Table C1), their toxic effects on the plants were not demonstrated, which is explained by the ability of trace elements to combine with organic matter. As a result, the chance of them being released from the sediment is much lower, making them less toxic (Baran et al., 2019). The higher GI index upstream of the HP for SA and LS may be due to the change in the distribution of components in the alluvia, for example, greater accumulation of nutrients necessary for plants upstream of a HP (Kabala et al., 2020; M. E. Rahman et al., 2020; Tomczyk & Wiatkowski, 2021; Vukosav et al., 2014).

It was observed that the sediment collected in spring had a more growth stimulating effect on plants than that collected in autumn (Figure 2), and Antunes et al. noted identical seasonal fluctuations in toxicity between spring and autumn in the plants tested (Antunes et al., 2007). On the other hand, Mankiewicz-Boczek et al. did not observe seasonal changes in toxicity between the spring and autumn seasons during their studies on river toxicity (Mankiewicz-Boczek et al., 2008).

### 4.3 Statistical significance test (Mann–Whitney U test)

The reduction of heavy metal concentration downstream of HPs was demonstrated, among others, by X. Zhao et al. (2018) in the Yangtze River, China; Shim et al. (2015), in Geum, South Korea; Aradpour et al. (2020) in Salaban, Iran (this study: results—Figures B5–B10, Appendix B, statistical analysis—Table D1, Appendix D). Among other parameters, the pH was also examined, and no changes were observed after the Klingenberg Dam on the Main River in Germany (Hahn et al., 2018), while there was a pH increase for the Vauassaie Dam on the Rhue River in France (Frémion et al., 2016), which is a correlation identical to that for the Ślęza River, and opposite to the Bystrzyca River (Figure B2, Appendix B). Regarding the granulometric composition, the results for the Klingenberg Dam in Germany (Hahn et al., 2018) and the Platanovrís Dam on the Nestos River in Greece (Kamidis & Sylaios, 2017) coincide with the results (Figure B1, Appendix B); more coarse-grained material (sand and clay) was recorded downstream of the dams, with silt upstream. This situation is due to the accumulation of large amounts of bottom sediments upstream of HPs, which are a vast storehouse of various substances (e.g., it has been estimated that 15% of the river phosphorus load is upstream of dams) (Maavara et al., 2015). In addition, the accumulation of fine-grained sediments rich in organic substances promotes the sorption of various substances, including HMs (Qu et al., 2019).

### 4.4 Differences between the studied parameters (PCA, HCA, and correlation matrix)

A number of studies have been carried out on the relationship between the upstream sediment parameters (the results of this type of analysis in this study: Figures 4 and 5; Appendix E). These include, for example, Wang et al. (2017)—Kelantan River, Malaysia; Kim et al. (2020)—Nakdong River, South Korea; Astatkie et al. (2021)—Avetu River, Ethiopia; Obolewski and Glińska-Lewczuk (2013)—Ślupia River, Poland. The results of other studies are different; for example, Rolka and Wyszkowski (2021) showed that in the studied soils, there is a significant correlation between Zn and Cd (compliance with this study), while for Pb and Ni there is none, which is inversely proportional contrary to the reported results. The inversely proportional correlation between heavy metals and D50 is because, as the particle diameter of the sediment decreases, its sorption capacity and ability to accumulate various types of substances increases. Exemplary studies confirming this claim were conducted in Chile (Parra et al., 2014), Russia (Minkina et al., 2011), China (He et al., 2016), Australia (Strom et al., 2011), Italy (Bartoli et al., 2012), and Nigeria (Aladesanmi et al., 2016). The interaction of all parameters can be modified by various factors, such as anthropogenic pressures that modify the physico-chemical properties of bottom sediments, the erosive action of rivers changing their granulometric composition, or chemical reactions occurring inside sediments, which affect the variability of the forms of various substances and their ability to migrate in the environment (Gabbud & Lane, 2016; Zhang et al., 2014).

### 5 CONCLUSIONS

The conclusions of the analysis are as follows:

1. Statistical significance was found for most parameters (p < 0.05) between the points upstream and downstream of the HPs on the Bystrzyca and Ślęza rivers (Cu, Ni, Cr, Zn, Pb, Cd, D50, EC, C:N). This means that HPs influence changes in the values of these parameters.

2. For both rivers studied, statistically significant relationships were observed between Cu, Ni, Cr, Zn, Pb, Cd, D50, pH, and EC (p < 0.05). Regarding the pairs of statistically significant parameters, a high correlation index (upstream 0.70) was observed in the Ślęza River between most HMS (exceptions: Cr/Cu, Zn/Cr, and Pb/Cr) and EC and heavy metals (except Pb) and pH. For the Bystrzyca River, high correlation indexes were also found between most HMS (exceptions: Pb/Ni, Pb/Cr, Pb/Zn, and Pb/Cd), pH/D50 and EC, and heavy metals, D50, and pH.

3. The calculated indices of the toxicity of HMs indicate that the most dangerous levels are the high concentrations of Cu, Ni, and Zn in the sediments upstream of the HP on the Ślęza River (the average class of the calculated indicators is 3.57, 3.29, and 3.00 on a scale up to 5.00, respectively). In this case, remediation is necessary, with phytoremediation recommended, or the use of synthetic...
zeolites. Considering all the average values for the calculated indices of HMS, one can rank sample sites from the cleanest to the most polluted as follows: Bystrzyca downstream < Ślęża reference < Bystrzyca reference < Ślęża downstream < Bystrzyca upstream < Ślęża upstream (respectively: 1.14 < 1.19 < 1.36 < 1.40 < 1.76 < 2.60).

4. In most cases, the heavy metal content decreases after passing through a HP, which results from changes in the granulometric composition and the accumulation of large sediment loads on damming weirs. These changes are as follows: Cu: Ślęża—average decrease of 13.44-times, Bystrzyca—1.63; Ni: 9.72 and 2.70; Cr: 5.51 and 0.83; Zn: 9.36 and 2.16; Pb: 5.71 and 0.64; Cd: a decrease from 1.69 to 0.0 mg kg⁻¹ which is a 0.74-fold change.

5. Usually, the tested bottom sediments stimulated growth in the tested plant species (Sinapis alba, SA; Lepidium sativum, LS; Sorghum saccharatum, SS) in comparison to the control samples. On the Ślęża River, for LS and SS, a growth stimulating effect on root development was found, which was better downstream from the HP (average values, respectively: GI-LS = 267.4% upstream from the HP and 275.1% downstream; GI-SS = 215.0% and 223.9%); for GI-SA, a growth stimulating effect was found upstream from the hydrotechnical structure, with no effect downstream (124.3% and 90.9%). For the Bystrzyca River, the results are convergent (LS, SS—stimulating effect, SA—no effect), and the average GI values are LS—131.3% and 148.5%, respectively; SS—246.4% and 273.5%; SA—90.4% and 105.4%; in this case, however, points downstream of the HP had more favorable results than upstream.

6. After passing through HPs, the granulometric composition of the sediment changes as follows—DS₀ higher, more coarse-grained formations (mainly sands) dominate, while upstream, fine-grained (clays and silts). Fine-grained materials have a greater tendency to absorb various substances, therefore, in most samples upstream of HPs, the concentration of pollutants is higher than downstream.

7. The C:N ratio increased downstream from HPs by an average of 37.11% for the Ślęża River and 10.88% for the Bystrzyca River. The median values of C:N ranged from 13.7:1 to 18.6:1, which are typical values for soils in this climate zone (12:1). The requirements for composts were not met (the optimal ratio is from 20:1 to 30:1), however, the sedimentary material can be used to enrich soils with typical values for soils in this climate zone (12:1). The requirements for composts were not met (the optimal ratio is from 20:1 to 30:1), however, the sedimentary material can be used to enrich soils with an excessively wide C:N ratio, for example, peat.

8. There was an anomalous relationship for the pH in the case of the Ślęża River, there was an increase in pH (in spring by 14.0%, in autumn by 7.64%), and in the Bystrzyca River, a decrease (spring—9.66%, autumn—12.65%). In the case of sediments from the Ślęża River, the pH is appropriate for the cultivation of most plants (average: 7.31), while for sediments from the Bystrzyca River (average: 5.22), it will have a negative impact on the development and growth of most species of cultivated plants (except for pineapples).

9. The values of EC decreased in most cases after passing through a HP: on average 10.13-times for the Ślęża River and 0.61-times for the Bystrzyca River. The EC values achieved in the sediments do not qualify the sediments as having a toxic effect on plant growth and development.

The conducted research shows that the tested bottom sediments do not meet the compost conditions (due to the low C:N ratio), however, phytotoxic tests prove that they can be used for the cultivation of selected species of crop plants (with a wide range of ecological tolerance). The greatest factor limiting the agricultural use of the tested sediment, apart from the low C:N ratio, is the high content of Cu, Ni, and Zn in the sediment above the Ślęża HP, as well as the low pH of the sediments from the Bystrzyca River (Kirk et al., 2010), unsuitable for most of the cultivated plants (exception: pineapples; Taira et al., 2005). However, acidic sediment could find other uses, for example, in the reclamation of alkaline soils in industrial areas, within a cement plant. The topic of the properties of bottom sediments within HPs is still poorly researched and requires in-depth analyzes, especially from a practical and interdisciplinary point of view.

**CONFLICT OF INTEREST**

The author declares that there is no conflict.

**DATA AVAILABILITY STATEMENT**

The data that supports the findings of this study are available in the supplementary material of this article.

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