



Assessing the Impact of a Hydropower Plant on Changes in the Properties of the Sediment of the Bystrzyca River in Poland

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This study aimed to assess the impact of a hydropower plant (HP) on the Bystrzyca River (left tributary of the Odra River, Poland) on selected parameters of the bottom sediment within this hydrotechnical structure. The following parameters were examined as part of the analyses: particle size distribution, pH, electrical conductivity (EC), and concentrations of Cd, Cu, Cr, Ni, Pb and Zn. Field studies were carried out upstream and downstream of the HP and at reference points. In addition, the risk of heavy metals in aquatic organisms was assessed using an ecotoxicological method. Based on the Wilcoxon signed-rank test, it was found that the HP influenced all of the parameters tested, except pH. Comparing the points closest to and downstream of the HP, an increase in the average grain diameter of D₅₀ (on average by 750%), and a decrease in the concentrations of most heavy metals: Ni (271%), Zn (216%), Cu (163%), Cr (83.0%), and Cd (74.2%), was observed. The ecotoxicological classification of heavy metal concentrations in sediments indicates, in most cases, little or no impact on aquatic organisms; the values of Ni and Zn in some samples upstream of the HP are exceptions, where remediation using synthetic zeolites, metal accumulation plants, or by electrokinetic methods, is necessary. Fine-grained fractions dominate the clays and sandy clays upstream of the hydropower plants, while sands, sandy clay loams, or sandy clays are dominated downstream. Frequent occurrence of skeletal fractions (>2.0 mm) was observed downstream, i.e., an average of 23.30% in each sample compared to 1.82% upstream of the HP, which is mainly due to greater anthropogenic pressure, especially tourism. The dominance of fine-grained fractions upstream of the HPs favors the accumulation of metals due to the high sorption capacity of these fractions. When comparing the analyzed groups of points, the average pH values are arranged in the following sequence: upstream HP (U) > downstream HP (D) > reference points (R), while EC has opposite values (i.e., U < D < R). This study may support sustainable sediment management and may allow for the development of recommendations related to the rational management of HPs.

Keywords: hydropower plants, environmental impacts, Bystrzyca river, sediment, metals, ecotoxicology, renewable energy sources, sustainable development

INTRODUCTION

Bottom sediments support the function of water-related and water-dependent ecosystems, and are home to various organisms. They store numerous organic and inorganic substances; however, some are pollutants such as metals (Rajfur et al., 2011; Alyazichi et al., 2017).

The sources of metals may be natural (e.g., from the geological structure of the surrounding area, the processes of weathering organic matter or atmospheric deposition) or artificial (e.g., sewage discharges, runoff from agricultural land, mines, landfills, urban areas) (Asaeda & Rashid, 2012; Usman et al., 2021). These elements are strongly adsorbed by the smallest fractions of sediments (silts and clays), and studies have shown that up to 99% of metals present in ecosystems can accumulate in sediments (Ndeda et al., 2017). Metals are dangerous because of their ability to migrate to various elements of the environment, such as water, sediment, and soil (Ahamad et al., 2020). Moreover, they exhibit low solubility (Capillo et al., 2018). They accumulate in organisms (no biodegradability) and combined with their toxic effects in the event of overdosing, they can seriously affect the health and life of organisms (Pagano et al., 2017; Dra et al., 2019; Miao et al., 2021). Because of such toxicity, monitoring areas exposed to metals is important (e.g., mining, industrial) (Manoj & Padhy 2014; Bhuyan et al., 2019), for introducing various remediation methods (i.e., neutralization by removing them from the environment or immobilization) (Peng et al., 2009; Cuske, Karczewska & Gałka 2017).

Hydropower plants located at the barrages separating rivers are also modifiers with regard to the transport conditions of the bottom sediment, including the spatial distribution of contained substances (Winton et al., 2019). Hydrotechnical structures constitute a transverse obstacle in river beds, seriously affecting the flow conditions and hydrological regime, geomorphological conditions, and living conditions of aquatic organisms (Li et al., 2012; Kasperek & Wiatkowski, 2014; Ashraf et al., 2018; Nistoran et al., 2018; Boulange et al., 2021; Kuriqi et al., 2021). Their action in relation to bottom sediments consists of their retention upstream of damming thresholds. It is estimated that more than 53% of the sediment flow worldwide is trapped in upstream dams (Wild and Loucks, 2014). As a result of this phenomenon, significant reduction in transported sediment load in rivers is observed in the downstream of dams with hydropower plants, affecting the function of aquatic and water-related ecosystems (Wiatkowski, 2010; Gabbud and Lane, 2016). For example, after the construction of the Great Aswan Dam in 1964 in the Nile Delta in Egypt, the transported net sediment load decreased from over 100 Mt annually to almost zero (Stanley and Clemente, 2011). Moreover, the capacity of suspended sediments in the Danube River (the Ceatal Izmail station) fell from 80 t/km² in 1931 to 30 t/km² in 1997 (Walling and Fang, 2003). Considering the sedimentary texture and composition, the average diameter of the sediment grains decreases with the distance from the hydropower plant, due to the decreasing transport capacity of the river (turbulent movement resulting from the phenomenon of

hydraulic bounce in downstream of the hydrotechnical structures) (Tomczyk et al., 2022). Additionally, increased erosion is observed downstream of the dams; for example, the annual amount of the material thus eroded ranged from $3.5 \cdot 10^3$ to $7.2 \cdot 10^3$ t in the Arc River (Antoine et al., 2020).

Because of the above-mentioned impacts of dams, developing solutions and technologies that enable the sustainable management of sediments is necessary; for example, the following three strategies are commonly adopted for dam reservoirs: directing sediments through or around the reservoir, removing sediments from the reservoir to regain their capacity, and minimizing the amount of sediment reaching reservoirs from the headwaters (Kondolf et al., 2014; Hauer et al., 2018; Katano et al., 2021). Conversely, implementing international energy policies is crucial; for example, the European Union planned to reduce greenhouse gas emissions by 2030, increase the energy efficiency of member states, and increase the share of renewable energy sources (including hydropower) in final energy consumption (European Parliament and the Council 2009; Arabatzis and Myronidis, 2011; Wiatkowski, Rosik-Dulewska and Tomczyk, 2017).

This study aimed to assess the impact of a hydropower plant on the Bystrzyca River (left tributary of the Odra River, Poland) considering selected parameters of the bottom sediment within this hydrotechnical structure. The following parameters were analyzed: particle size distribution, pH, electrical conductivity (EC), Cd, Cu, Cr, Ni, Pb and Zn. In addition, the risk of metals on aquatic organisms was assessed using an ecotoxicological method. The need for sediment remediation was determined, which is in line with the assumptions of sustainable sediment management. This study is an important contribution to research on the environmental impacts of hydropower plants, which may facilitate future recommendations for the rational management of such facilities. The issues raised are important from the social, economic, and environmental perspectives. There has been little research on the influence of hydropower plants on the properties of river sediments.

MATERIALS AND METHODS

Field Research

Field tests were carried out in two series of measurements, in spring and autumn of 2019. Bottom sediment was collected at points located on the Bystrzyca River (left tributary of the Odra River, Poland), near the Sadowice hydropower plant (51°03'15"N 16°47'42"E—51°03'22"N 16°47'49"E) and at reference points in Sadowice and Małkowie (51°03'30"N 16°47'51"E and 51°04'39"N 16°49'05"E). The hydropower plant is located 26.05 km from the mouth of the Bystrzyca River, and has a capacity and damming height of 0.06 MW and 1.8 m, respectively; it began operating in 1921 (Tomczyk and Wiatkowski, 2021). The locations of the test area and sediment sampling points are shown in **Figure 1**.

Bottom sediments were collected from the near-surface layer, approximately 5 cm thick, using a 2,500 cm³ Van Veen grab

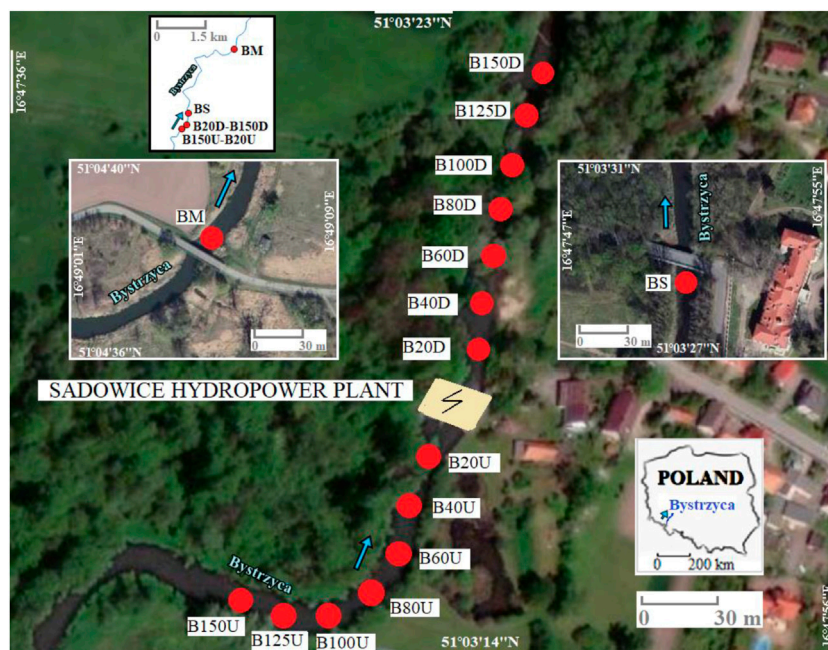


FIGURE 1 | Location of the sediment sampling area on the Bystrzyca River (B—Bystrzyca River, numbers—distance from the hydropower plant, U—point upstream the hydropower plant, D—point downstream the hydropower plant, M—Malkowice, S—Sadowice).

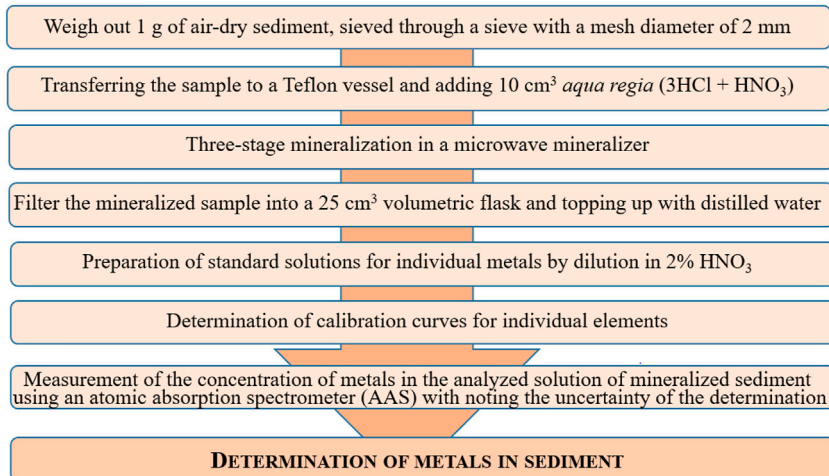


FIGURE 2 | Procedure for the determination of metals in the investigated sediment.

sampler. The samples were then transferred to polyethylene bags and transported to the laboratory in a refrigerator (Duodu, Goonetilleke and Ayoko 2016).

Laboratory Tests

The sediment samples delivered to the laboratory were stored at room temperature and protected from sunlight. Bottom sediment samples dried under such conditions were tested for their particle size distribution (the Bouyocous areometric method modified by Casagrande and Prószyński) (Bojko et al., 2017; Waroszewski

et al., 2019), metals such as Cu, Ni, Pb, Cr, Zn, and Cd (mineralization in aqua regia, atomic absorption spectrophotometry (AAS) (Sarmani 1989; He, Shi & Wu 2016), conductometer, and pH (the potentiometric method in water). The research was carried out in the laboratory of the Institute of Soil Sciences, Plant Nutrition and Environmental Protection of the Wrocław University of Environmental and Life Sciences. The procedure for the determination of metals and the particle size distribution of the tested sediment is presented in **Figures 2, 3**.

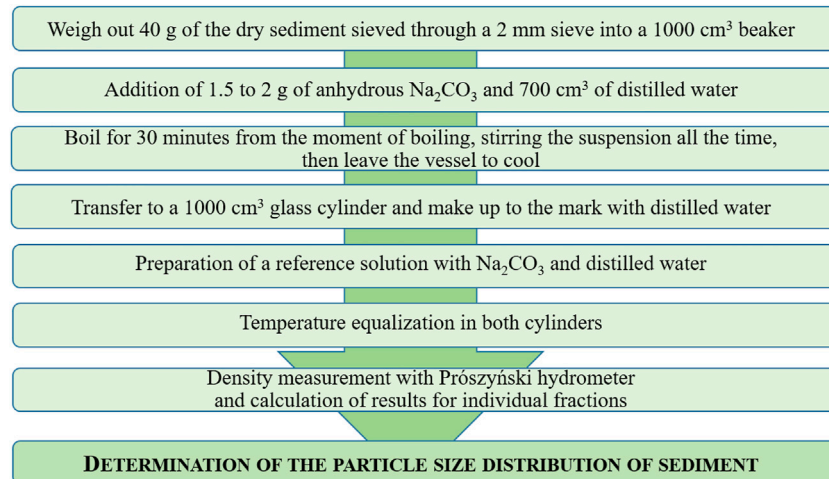


FIGURE 3 | Procedure for the determination of the particle size distribution of investigated sediment.

Data Analysis

The classification of the grain size composition was determined on the basis of its texture, i.e., the ratio of the content of silt (≤ 0.002 mm), clay (0.002–0.05 mm), and sand (0.05–2.0 mm), summed up to 100% (Bieganowski et al., 2013; Kruczkowska et al., 2020). The soil taxonomy established by the United States Department of Agriculture and the National Cooperative Soil Survey (USDA classification) was used (Arfania et al., 2018; Borselli et al., 2008). The following are the types of soil: sand, loamy sand, sandy loam, sandy clay loam, sandy clay, loam, clay loam, clay, silty clay, silty clay loam, and silt. The study also presents the division of sediments into sediment skeleton particles (> 2.0 mm) and fine Earth (≤ 2.0 mm). Additionally, the mean particle diameter of the bottom sediment (D_{50}) in the Earth parts of the tested sediment samples was calculated for determining the weighted average for the upper values of the diameters in the designated ranges (i.e., 0.002, 0.006, 0.02, 0.05, 0.1, 0.25, 0.5, 1.0, and 2.0 mm).

The content of metals in the sediments was assessed in terms of their potential toxicity to aquatic organisms, using the ecotoxicological method (MacDonald et al., 2000; Tomić et al., 2019; Jaskuła et al., 2021; Wdowczyk et al., 2022). The method distinguishes three levels of toxicity characteristics:

- Threshold effect concentration (TEC): maximum content of the element that does not adversely affect benthic organisms.
- Probable effect concentration (PEC): concentration at which the negative effect of the substance on benthic organisms becomes noticeable.
- Midpoint Effect Concentration (MEC): mean of TEC and PEC values.

Based on the determined levels of TEC, MEC, and PEC, four classes of metal toxicity can be distinguished: in class I, there are no symptoms of toxicity; in II and III, toxicity may occur with

varying severity; in IV, toxicity is certain. **Table 1** presents the ecotoxicological classifications of the tested metals.

To illustrate the potential impact of the hydropower plant, the percentage difference between the results obtained for the sediment samples located closest to the hydropower structure (i.e., at a distance of 20 m from the hydropower plant) was calculated. Additionally, the results were sorted according to the sediment collection date.

This article presents basic descriptive statistics for all determined parameters (minimum, maximum, mean, and standard deviation). The statistical significance of the results between the two groups of points (upstream and downstream of the hydropower plant) was also tested using the two-tailed Mann–Whitney U test (Wilcoxon signed-rank test). Therefore, assessing the parameters influenced by the operation of the hydrotechnical construction is possible. The null hypothesis for this test is that the medians in both study groups are equal, and the distribution of the dependent variables does not match the normal distribution. The test calculates U and z -ratio values using the formulas presented in **Table 2** (significance level $p < 0.01$ and $p < 0.05$) (McKnight et al., 2010).

The analyses were performed using Statistica 13 (Dell Computer Corporation, 2021), SPSS Statistics 26 (IBM Corporation, 2019), OriginLab Corporation, 2021 (OriginLab, Northampton, MA, United States; boxplots) and Office 2013 (Microsoft Corporation, 2013). The area was mapped using QGIS 2.8.4 (QGIS Development Team, 2015; Open Source Geospatial Foundation Project). The analytical procedure used in the article is shown in **Figure 4**.

RESULTS AND DISCUSSION

Basic Statistics

The values of the examined parameters varied within the range, as shown in **Table 3**. With regards to the average values, the following parameters decreased at points downstream of the

TABLE 1 | Classification of metals in sediments using the ecotoxicological method.

Parameter (mg/kg)	≤ TEC (1st class)	> TEC ≤ MEC (2nd class)	> MEC ≤ PEC (3rd class)	> PEC (4th class)
Cd	0.0–0.99	1.00–3.00	3.01–5.00	>5.00
Cu	0.0–32.0	32.1–91.0	91.1–150.0	>150.0
Cr	0.0–43.0	43.1–76.5	76.6–110.0	>110.0
Ni	0.0–23.0	23.1–36.0	36.1–49.0	>49.0
Pb	0.0–36.0	36.1–83.0	83.1–130.0	>130.0
Zn	0.0–120.0	120.1–290.0	290.1–460.0	>460.0

TABLE 2 | The method of calculating parameters in the Mann-Whitney U Test.

Parameter	Equation	Description
U value	$U = \frac{n(n+1)}{2} - \sum_{ranks}$	- n—the number of items in the samples - \sum_{ranks} —the sum of ranks in the sample
z-ratio	$z = \frac{U - \sigma_U}{\sigma_U}$	- σ_U – the standard deviation of U - x_U – the mean of U

hydropower plant compared to the points upstream of the hydropower plant: EC (change by 112%), Cd (232%), Cr (145%), Cu (227%), Ni (208%), Pb (131%) and Zn (241%), and an increase in D50 (489%) and pH (17.90%). Considering the groups of points in relation to the reference points, mean values for D50, Cu, Ni, Cr, Zn, and Cd were observed, the highest for pH and Pb, and the lowest for EC. Detailed analyses are

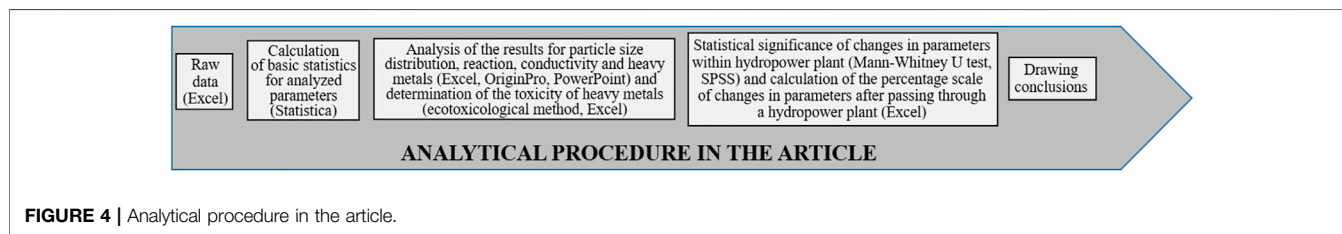


FIGURE 4 | Analytical procedure in the article.

TABLE 3 | Basic statistics of the results obtained for the tested parameters in the sediments of the Bystrzyca River.

Parameter	Location	Min	Max	Av	SD
D ₅₀ (mm)	Upstream hydropower plant	0.010	0.084	0.027	0.022
	Downstream hydropower plant	0.024	0.241	0.162	0.059
	Reference points	0.022	0.183	0.104	0.063
pH	Upstream hydropower plant	3.31	6.02	4.58	0.80
	Downstream hydropower plant	3.92	7.65	5.40	1.23
	Reference points	4.91	6.96	5.87	0.74
EC (μS/cm)	Upstream hydropower plant	118.5	870.0	513.6	285.6
	Downstream hydropower plant	33.8	712.0	242.0	228.4
	Reference points	57.3	420.0	190.6	104.7
Cd (mg/kg)	Upstream hydropower plant	0.00	1.92	1.13	0.51
	Downstream hydropower plant	0.00	1.55	0.34	0.49
	Reference points	0.00	1.64	0.69	0.60
Cr (mg/kg)	Upstream hydropower plant	9.91	47.31	31.86	12.22
	Downstream hydropower plant	0.43	38.15	13.00	12.57
	Reference points	7.06	33.28	20.37	11.50
Cu (mg/kg)	Upstream hydropower plant	9.52	72.29	37.88	16.47
	Downstream hydropower plant	2.16	40.38	11.58	11.09
	Reference points	3.31	49.23	24.00	15.78
Ni (mg/kg)	Upstream hydropower plant	7.24	48.49	30.47	12.07
	Downstream hydropower plant	3.56	27.97	9.89	8.56
	Reference points	6.36	28.78	15.82	8.26
Pb (mg/kg)	Upstream hydropower plant	2.29	32.06	17.62	9.21
	Downstream hydropower plant	2.46	21.28	7.63	5.12
	Reference points	3.15	55.09	18.83	16.25
Zn (mg/kg)	Upstream hydropower plant	35.94	320.37	173.60	78.62
	Downstream hydropower plant	11.03	197.90	50.89	50.75
	Reference points	20.36	151.55	86.14	51.68

Designations in the table: min, minimum value; max, maximum value; av, average value; SD, standard deviation.

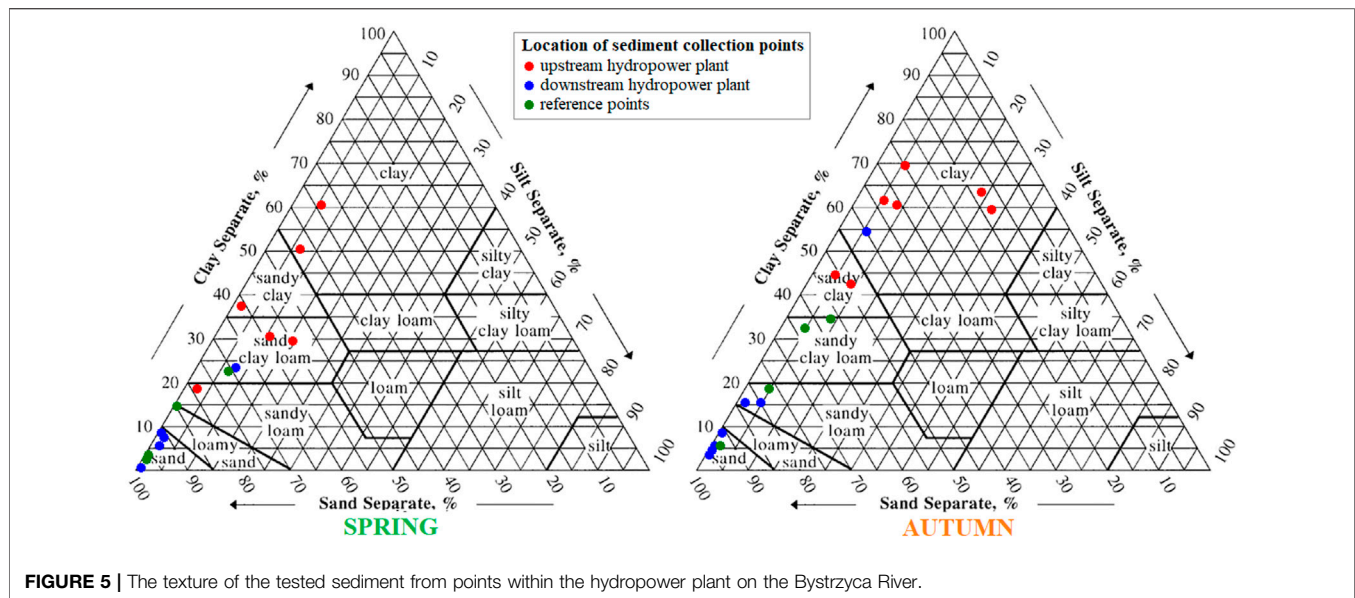


FIGURE 5 | The texture of the tested sediment from points within the hydropower plant on the Bystrzyca River.

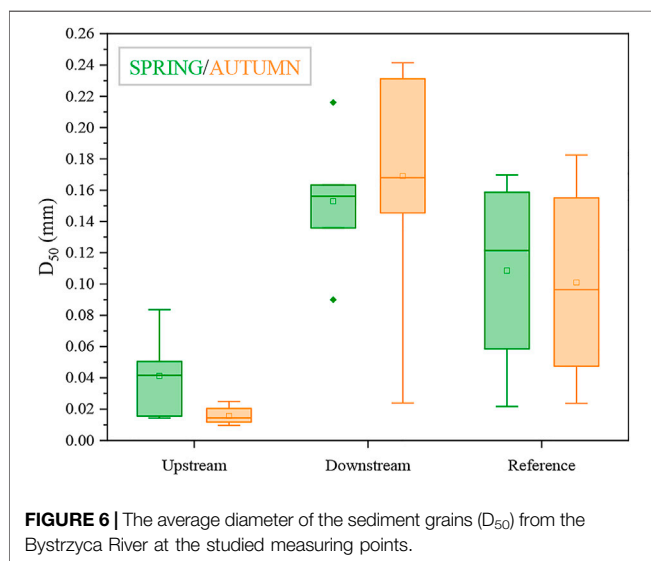


FIGURE 6 | The average diameter of the sediment grains (D_{50}) from the Bystrzyca River at the studied measuring points.

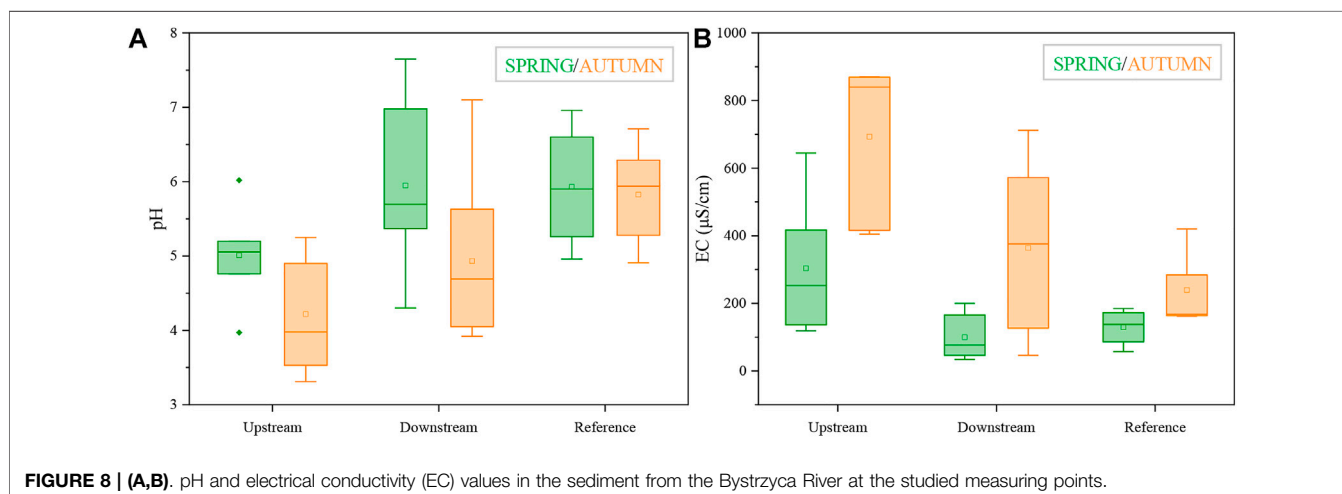
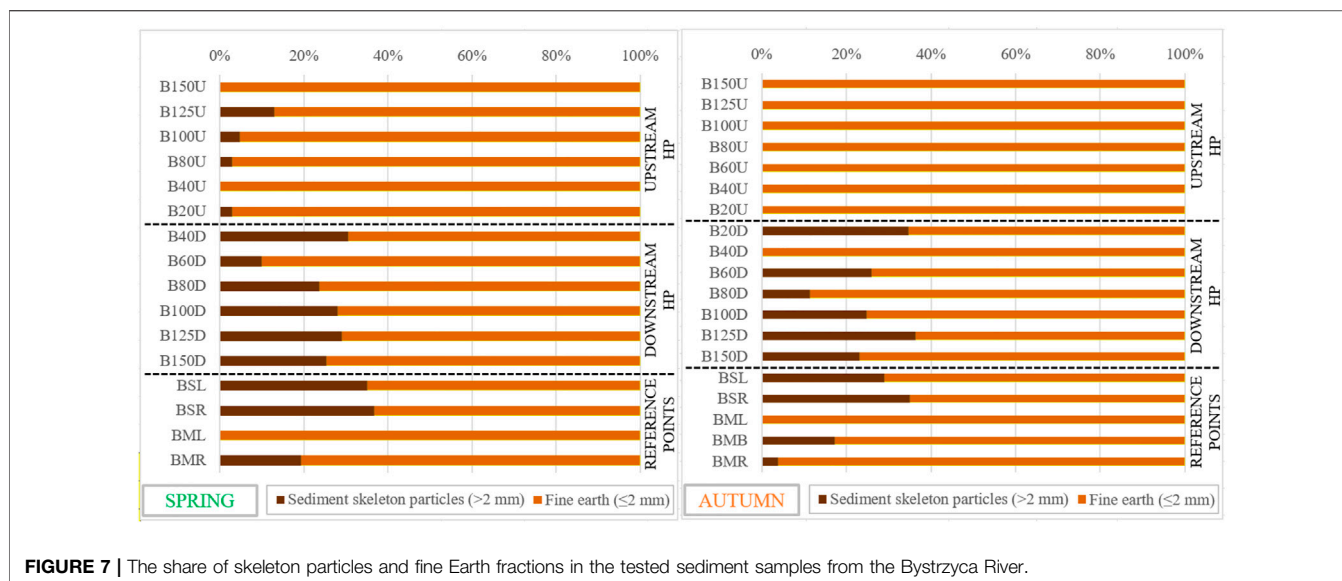
presented in *Particle Size Distribution and Changes in Parameter Values Within a Hydropower Plant*.

Particle Size Distribution

The texture of the investigated sediment differed between the upstream and downstream points of the hydropower plant and the reference points. In upstream of the hydropower plant, the sediment belonging to clays or sandy clays dominated; sediment belonging to sands, sandy loams and clay dominated in the downstream; at reference points, sediments belonging to sands, sandy clay loams, or sandy clays, dominated. The results varied between seasons; in spring, the texture was more concentrated in coarse sands and loams, while in autumn, it was more heterogeneous and also counted among the clays (Figure 5).

A significant increase in D_{50} is visible downstream of the hydropower plant, regardless of the season (Figure 6). The reference points represent the full cross-section of the sediment grading, which is intermediate between the compared groups. Considering seasons, there was a decrease in the D_{50} particle size upstream of the hydropower plant (spring: 0.108 mm, autumn: 0.101 mm) and at the reference points (spring: 0.041 mm, autumn: 0.016 mm), while an increase was observed downstream of the hydro-engineering structure (spring: 0.152 mm, autumn: 0.169 mm). Considering the reference points, there was a similar dispersion of the D_{50} values between the seasons, while in the remaining points there were differences between spring and autumn (upstream of the hydropower plant in spring: 0.014–0.084 mm, autumn: 0.010–0.025 mm; downstream the hydropower plant in spring: 0.090–0.216 mm, autumn: 0.024–0.241 mm).

The reflection of the previous results can also be seen in the fraction of gravel and stones, i.e., with a diameter greater than 2 mm (Figure 7). A higher percentage of coarse grains was recorded at downstream of the hydropower plant and at the reference points, than at upstream of the hydropower plant (average total share: 23.30, 19.61, 1.82%). The results differ depending on the season, especially at upstream of the hydropower plant, skeleton particles were recorded in spring (an average share of 3.94% in the studied sediments), while in autumn, they were not observed. For the remaining points, the differences were small. The coarse-grained fraction included gravel, stones, branches, leaves, and waste, which accumulated mainly downstream of the hydropower plant and at reference points, due to trees and shrubs overgrowing the banks of the watercourse, and anthropogenic pressure (mainly tourism and recreation, artificial beaches, canoeing, fishing, and recreation for local residents). This phenomenon is caused by a lower water depth downstream of the damming than upstream, and the pressures mentioned are greater there (there are better



conditions for safe use of the river, e.g., for bathing purposes). In addition, the effect of the hydraulic jump is influencing, causing the formation of a vortex motion, so that directly downstream the damming, more boulders, stones and gravel are visible, carried along with the river current 125.5 mm (38.1).

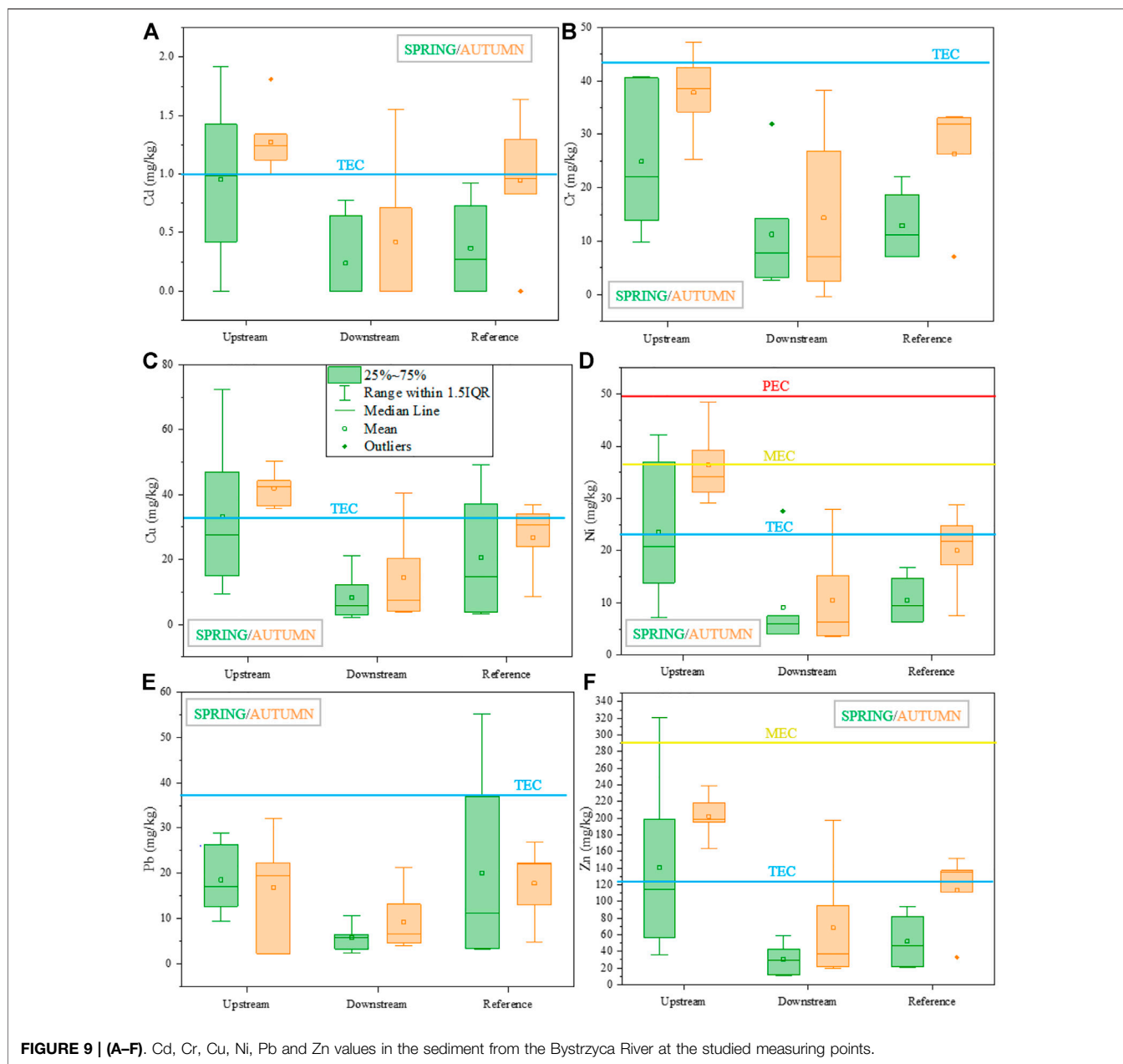
pH and Electrical Conductivity

The pH values were lower during autumn than in spring at each point. Additionally, the values are in the following order: reference points > downstream hydropower plants > upstream hydropower plants. The mean values of the reaction were strongly acidic (<5.0; upstream of the hydropower plant and downstream of the hydropower plant in autumn) or acidic (5.0–6.0; downstream of the hydropower plant in spring and at reference points) (Jaggi et al., 2005). The ranges of the 25th to 75th percentile values downstream of the hydropower plant and at the reference points were similar in both seasons, and upstream of the hydropower plant, the amplitude differed markedly (spring: 0.36, autumn: 1.19). **Figure 8A** presents the described pH dependencies.

After passing the hydropower plant, decreases in conductivity were recorded, while at the reference points, these values were intermediate (spring) or lowest (autumn). In autumn, the conductivity increased compared to that in the spring. This may reflect the greater amount of pollutants accumulated during the growing season (e.g., dead organic matter and debris). The amplitude of the conductivity value was higher in autumn than in spring in each group of points, considering the range from the 25th to 75th percentile (upstream of hydropower plant: 253 $\mu\text{S}/\text{cm}$ in spring; 352 $\mu\text{S}/\text{cm}$ in autumn; downstream of hydropower plant: 92.5 $\mu\text{S}/\text{cm}$ in autumn, 390 $\mu\text{S}/\text{cm}$; reference points: 65.6 $\mu\text{S}/\text{cm}$ in spring; 151 $\mu\text{S}/\text{cm}$ in autumn). **Figure 8B** shows the variation in the conductivity across the described point groups.

Metals

Regardless of the season, the average concentration of each of the tested metals decreased downstream of the hydropower plant



(Figures 9A–F). At the reference points, the values were indirectly developed. In most cases, higher concentrations of elements were observed during autumn, potentially attributed to the accumulation of various pollutants in the bottom sediment during the growing season. The decrease in the D_{50} value upstream of the hydropower plant and at the reference points may also be significant. A higher concentration of fine-grained fractions favors the sorption of various impurities (Buyang et al., 2019). In addition, the upstream damming conditions are conducive for the accumulation of large loads of various substances, and water zones with limited flow significantly lower sediment transport capacity are created, in contrast to the zones downstream damming, where the current is rapid and hydraulic bounce occurs (Ali et al., 2019; Tomczyk &

Wiatkowski, 2020). Moreover, various studies have proved that mainly sand fractions pass through the damming thresholds, not clay and silt, which show strong sorption capacity (Yao et al., 2015; Bao et al., 2020). In addition, the mechanisms of the properties of metals in sediments are also influenced by the content of organic carbon or geological properties (Zhang et al., 2014; Jokinen et al., 2020).

Regarding the ecotoxicological classification, most of the sediment samples as compared to the concentration of the metals tested, did not pose a risk to aquatic organisms (class I, values lower than or equal to TEC); an adverse effect on these organisms is possible, but the risk is low (class II; values higher than TEC but less than or equal to MEC). The concentrations of Ni and Zn in some of the samples

TABLE 4 | Summary of the results of the Mann–Whitney *U* test for the tested parameters between the sections upstream and downstream of the hydropower plant on the Bystrzyca river.

Parameter	Upstream			Downstream			Combined			U ¹	Z
	Σranks	Xranks	U	Σranks	Xranks	U	Σranks	Xranks	σ		
D ₅₀	96	7.38	164	255	19.62	5	351	13.5	19.5	5**	-4.051**
pH	143	11	117	208	16	52				52	-1.641
EC	224	17.23	36	127	9.77	133				36*	2.461*
Cd	237	18.23	23	114	8.77	146				23**	3.128**
Cr	246	18.92	14	105	8.08	155				14**	3.590**
Cu	244	18.77	16	107	8.23	153				16**	3.487**
Ni	247	19	13	104	8	156				13**	3.641**
Pb	260	20	0	91	7	169				0**	4.308**
Zn	244	18.77	16	107	8.23	153				16**	3.487**

Designations in the table: ¹ critical value of *U* at $p < 0.01$ is 34 and at $p < 0.05$ is 45; ** significant at p value < 0.05 , * significant at p value < 0.01 (2-tailed).

upstream of the hydropower plant are anomalies, which may have negative consequences for aquatic organisms, and the risk of these consequences is higher (class III) or reaches values close to the toxic (class IV, PEC). Considering the groups of points, the most unfavorable results were recorded upstream of the hydropower plant, especially in autumn (except for Pb). The average metal concentrations were higher during autumn.

Assuming that for classes III and IV, remediation measures should be taken for removing or immobilizing Ni and Zn (Kabała et al., 2020; Zhao et al., 2020). In the first group of methods, pollutants travel from the solid phase to the sediment solution, while in the second group, they are retained in the solid phase (recommended methods) by changing the properties of the sediment (methods not recommended due to the risk to the environment) or a combination of these two methods (Ou et al., 2018; Chen et al., 2020). Considering Ni and Zn, using synthetic zeolites with high sorption capacity (in the form of briquettes that immobilize easily soluble forms of metals accumulated in the sediment) (Ali et al., 2019; Cataldo et al., 2021; Szerement et al., 2021), phytoremediation using plants that accumulate large amounts of such elements in their tissues without a noticeable phytotoxic effect (hyperaccumulators, e.g., energy willow) (Giordani et al., 2005; Sainger et al., 2014; Wu et al., 2021), and electrokinetic methods using the electric field generated by the flow of current, as a result of which the pollutants travel toward the appropriate electrodes on which they precipitate (Saleem et al., 2011; Hawal et al., 2021; Kamal et al., 2021), are recommended.

Changes in Parameter Values Within a Hydropower Plant

The statistical analysis carried out using the Wilcoxon signed-rank test indicates that the results upstream and downstream of the hydropower plant differ significantly for most of the parameters studied. By sorting the obtained *U* values in ascending order, the following values were obtained: Pb < D₅₀ < Ni < Cr < Cu, Zn < Cd (significance for $p < 0.01$), and EC ($p < 0.05$). No statistically significant relationships were found for pH (Table 4).

When analyzing the percentage changes in the values between the points located directly upstream and downstream of the hydropower plant, convergent relationships were observed for seven of the nine parameters considered (Figure 10). The biggest changes concern the D₅₀ value; in autumn, downstream of the hydropower plant, values were higher by almost 1,300%, and by over 220% in spring. For Cd, Cr, Cu, Ni, and Zn, there was a decrease in value after passing through a hydropower plant; these changes were lower in the fall than in the spring. The largest changes in concentrations were observed for Ni (approximately 270%) and Zn (approximately 270 and 165%), and the smallest changes were observed for Cd (82 and 66%). Considering Pb, pH, and EC, the same trend was not observed in both seasons of the year; for Pb and EC, the decreases occurred in spring, while for pH, the opposite trend was observed. However, as mentioned earlier, the results for Pb and EC are statistically significant in relation to the results from all consumption points upstream and downstream of the hydropower plant, treated as two groups of dependent variables.

Most of the obtained results were consistent with those of other studies. The accumulation of metals in sediments upstream of dams (also having an energetic function) has been reported, for example, in studies at the Three Gorges Dam on the Yangtze River in China (Zhao et al., 2017), the Geum River dams in South Korea (Shim et al., 2015) or dams on the Sabalan River in Iran (Aradpour et al., 2020).

It was also observed that after passing through a hydropower plant, the texture of the bottom sediment is coarser, belonging to the sand or clay fraction, and upstream, usually to silt [e.g., studies at the Klingenberg dam in Germany (Hahn et al., 2018) or at the Platanovrisi dam] on the Nestos River in Greece (Kamidis and Sylaios, 2017). This is due to the accumulation of large amounts of sediments upstream of hydropower plants, which are a large storehouse of various substances (e.g., it has been estimated that 15% of the world's river phosphorus load is upstream dams) (Maavara et al., 2015).

The results are different with regards to pH; for example, at the Vaussaire dam on the Rhue River in France and at the hydropower plant on the Ślęza River in Poland, the value for pH increased by an average of 18.9% and by 6.26% downstream of the damming (Fremion et al., 2016; Tomczyk et al., 2021),

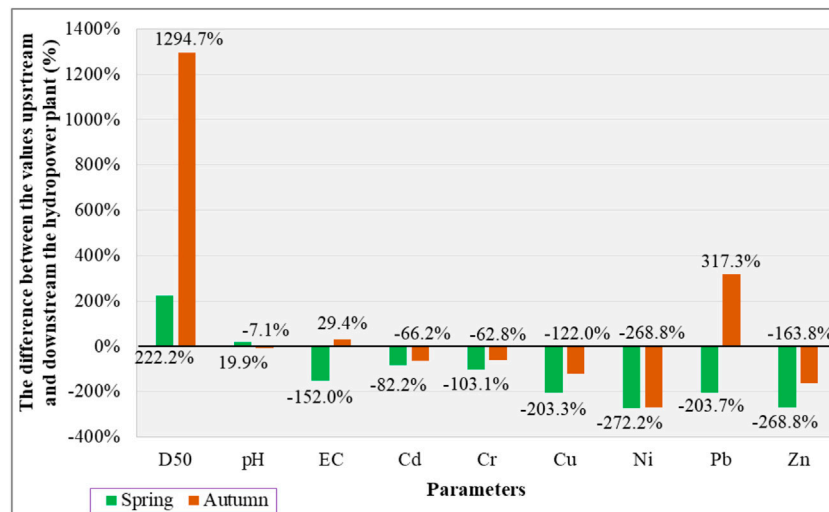


FIGURE 10 | Percentage changes in the values of bottom sediment parameters—comparison of the results from the points located closest to the hydropower plant on the Bystrzyca River.

whereas at the Klingenberg Dam in Germany, no changes were observed (Hahn et al., 2018).

CONCLUSION

The conclusions from the analysis presented in the article are as follows:

- Hydropower plants influenced eight of the nine tested parameters. Based on the Wilcoxon signed-rank test, statistical significance was found for the mean grain diameter (D₅₀), Pb, Ni, Cr, Cu, Zn, Cd, and EC. No statistical significance was found for pH.
- Comparing the points closest and downstream to the hydropower plant, an increase in D₅₀ (on average by 750%), and a decrease in the concentrations of most metals Ni (271%), Zn (216%), Cu (163%), Cr (83.0%), and Cd (74.2%), was observed.
- The ecotoxicological classification of metal concentrations in sediments indicates, in most cases, little or no impact on aquatic organisms (class I or II). The values of Ni and Zn in some samples upstream of the hydropower plant are anomalies, where the risk of adverse effects on aquatic organisms was higher (class III or IV). It requires remediation with the use of synthetic zeolites, metal accumulating plants (hyperaccumulators), or by the electrokinetic method.
- Upstream of the hydropower plant, fine-grained fractions dominate clays or sandy clays, while in the downstream, mainly sands are dominated, less often sandy clay loams or sandy clays. In addition, downstream of the hydropower plant, a more frequent occurrence of skeletal fractions (>2.0 mm) was found, i.e., an average of 23.30% in each sample compared

to 1.82% upstream of the hydropower plants. This is mainly due to greater anthropogenic pressure, especially from tourism (these fractions often include waste). The dominance of fine-grained fractions upstream of the hydropower plant favors the accumulation of metals due to the high sorption capacity of these fractions.

- When comparing the analyzed groups of points, the average pH values are arranged in the following sequence (regardless of the season): upstream hydropower plant (U) > downstream hydropower plant (D) > reference points (R), and vice versa, i.e., U < D < R. Lower pH and higher conductivity were observed in each point group during autumn. The mean pH values of the tested samples were strongly acidic or acidic (pH ≤ 6.0).
- This research agrees with the current issues of the sustainable use of sediments deposited within hydropower plants.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Conceptualization, BG, MW, and PT; methodology, BG and PT; software, PT; validation, BG and PT; formal analysis, PT; investigation, BG, ŁG, MW, and PT; resources, BG and PT; data curation, PT; writing—original draft preparation, PT; writing—review and editing, BG and MW; visualization, PT; supervision, BG and MW.

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