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Analysis of Spatial Distribution of Sediment Pollutants Accumulated in the Vicinity of a Small Hydropower Plant

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Abstract: Hydropower plants affect the distribution and composition of sediments. The main aim of this study was to analyze the spatial distribution of sediment pollution in the vicinity of a small hydropower plant. The grain composition of the sediments, the content of heavy metals (Cu, Ni, Cr, Zn, Pb, and Cd) and select physicochemical properties (pH, electrolytic conductivity) were tested at 14 points upstream and downstream of the hydropower plant on the Ślęza River in Poland, as well as at reference point. The interactions between the tested parameters were also verified. The results of the conducted analysis show that hydropower plants significantly affect the composition and properties of sediments. Large amounts of sediment are deposited on damming weirs, accumulating heavy metals and other substances. The differences in the concentrations of elements were significant, and Cu, Ni, Cr, Zn and Pb were 8.74, 9.53, 3.63, 8.26 and 6.33 times higher, respectively, than the median value at points upstream of the hydropower plant than downstream. It was shown that the tested parameters of the sediments interact with each other and are correlated; heavy metals showed a synergistic effect, while other parameters configurations showed an antagonistic effect. The higher content of heavy metals upstream of the hydropower plant resulted from the presence of finer sediment—classified as silt—in this section. Downstream of the hydropower plant, there were mainly sands, which showed a lower ability to absorb substances. This work contributes to improving the rational management of the worldwide issue of sediments within dams located in river valleys. Moreover, it is in line with the 2030 Sustainable Development Goals adopted by the United Nations, particularly in the fields of clean water and sanitation, clean and available energy, and responsible consumption and production.

Keywords: hydropower plants; sediment; environmental impacts; heavy metals; dams; rivers; renewable energy sources; water management; sustainable development

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1. Introduction

Dams, including those with hydropower functions, significantly affect the distribution and composition of bottom sediments in river systems and contribute to the energy balance [1–4]. This effect is especially noticeable in the context of sediment accumulation upstream of the dams, due to the partition of the riverbed, as well as increased erosion processes downstream of the dams [5,6].

Research shows that 28% of the world's sediment stocks (4–5 Bt per year) are stored in reservoirs upstream of dams, taking into account all river basins [7,8]. This has a number of consequences, including impacts on the sections downstream of the dams, where the phenomenon of sediment starvation ("hungry waters") occurs [9,10]. Sediments are both the building blocks of water-related environments, due to their role in shaping geomorphological characteristics [11,12], and a habitat for many organisms; that is, a place for shelter and reproduction, as well as a food base [13,14]. Due to the significant amounts of sediment that are trapped, rivers transport much smaller sediment loads to their lower sections. For example, the net sediment load delivered to the Nile delta in Egypt is now practically zero, following the construction of the Great Aswan Dam in 1964; previously, it was 100 to 124 Mt of sediment per year [15,16]. A reduction or absence of sediment loads in the lower sections of rivers have also been reported; for example, in the Colorado River delta in the United States and Mexico [17,18], the Yangtze in China [19], the Mekong in Cambodia [20], and in rivers of the Mediterranean and Black Seas [21].

One result of the existence of transverse obstacles is a change in the distribution of chemical components stored in alluvia, both nutrients necessary for the life of organisms and trace elements that may pose a threat to the functioning of ecosystems, such as heavy metals [22–24]. For example, it is estimated that about 15% of the river phosphorus load is upstream of dams [25]. The sediments themselves can accumulate up to 99% of heavy metals present in ecosystems [26]. The retention of fine fractions (silts and clays) upstream of the dams is noted, while downstream, the greater percentage comprises coarse-grained fractions, especially sands. Sands, due to the greater share of mineral parts, usually constitute the building blocks of river ecosystems and do not accumulate nutrients to such a large extent as the fine fractions [7,27]. In addition, coarser fractions, such as stones and gravel, are mechanically retained at the damming weirs. As a result of the effect of the hydraulic jump phenomenon and the decreasing flow velocity downstream of the dams, sediment particle diameters decrease as they move away from hydroelectric power plants [28].

The main aim of this study was to analyze the spatial distribution of bottom sediment pollution in the vicinity of a small hydroelectric power plant. For this purpose, in the spring and fall 2019, tests were carried out on the granulometric composition of the sediments, the content of heavy metals (Cu, Ni, Cr, Zn, Pb and Cd), as well as select physicochemical properties (pH, electrolytic conductivity) at points upstream and downstream of the hydropower plant on the Ślęza River in Poland, as well as at reference points. The interactions between the tested parameters were also verified (Mann–Whitney U test, Pearson correlation coefficient).

The importance of this work is its contribution to improving the rational management of bottom sediments within dams located in river valleys, which is a global issue [29]. This research is in line with the 2030 Sustainable Development Goals adopted by the United Nations [30,31], especially in the areas of clean water and sanitation, clean and available energy, and responsible consumption and production. In addition, heavy metals are considered priority substances in the field of water policy, in accordance with the European Union's Water Framework Directive (Directive 2000/60/EC; the management of these pollutants is of particular importance for the implementation of its assumptions due to the dangers they may pose to the aquatic environment) [32,33].

The innovation of this article is the temporal and spatial analysis of the variability of selected parameters characterizing bottom sediments within a run-of-river hydroelectric power plant. In the future, these results can be used to create a hydrodynamic model of pollution propagation within this type of hydrotechnical facilities, which may be useful for the above-mentioned social, economic and environmental reasons. To date, most research has focused on the operation of dam reservoirs or dams themselves, rather than the effects of hydropower on sediment properties.

2. Materials and Methods

The studies of sediments were carried out in the lower reaches of the Ślęza River, in the area of Wrocław and Rzeplin (Poland). They were performed in April and October 2019. Research points located upstream and downstream of the hydroelectric power plant in Wrocław were selected for the analysis and samples were collected at distances of 20, 40, 60, 80, 100, 125 and 150 m away from the hydrotechnical structure (2.85–3.15 km away from the mouth of the Ślęza river), as well as at reference points in Rzeplin, 21.5 km away from the river's mouth (a reference point selected in a natural section of the river with a high degree of habitat, geomorphological diversity, etc.; the properties of the sediments reflect these characteristics). Samples of the top layer of hydrated bottom sediments were taken using a Van Veen sampler with a capacity of 2500 cm^3. The samples were transferred to appropriately marked polyethylene bags, which were then transported under refrigeration to the laboratory [34]. The locations of the sampling points at the hydropower plant are shown in Figure 1.

Figure 1. Sediment sampling points of the hydropower plant in Wrocław on the Ślęza River.

Prior to analysis, the samples were stored at a temperature of about 20 °C and protected from sunlight. After the samples were placed in a fume hood and dried in the air, they were marked in terms of their granulometric composition using the Bouyoucos areometric method modified by Casagrande and Prószyński [35,36]. The samples were mineralized in aqua regia and atomic absorption spectrophotometry (AAS) determined their heavy metal content, including the elements Cd, Cr, Cu, Ni, Pb and Zn [37–39]. The conductivity of the sediments was determined using a conductometer, and their pH was determined by the potentiometric method in water.

The grain sizes were classified according to the classification standards of the Polish Society of Soil Science of 2008 [40]. The following fractions with the assigned particle diameters were distinguished: rock fragments > 2 mm were boulders, stones, or cobbles; fine earth parts < 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 earthy fractions, specific groups and granulometric subgroups were distinguished [41,42].

To calculate the average grain diameter (Øav.) of the fine earth parts (up to 2 mm), the percentage of fractions with a given grain diameter was multiplied by the value of the upper grain size limit for each of them (i.e., 0.002, 0.006, 0.02, 0.05, 0.1, 0.25, 0.5, 1.0 and 2.0 mm). These values were summed and divided by the sum of the weights to obtain the average values.

As part of the in-depth analyses, the statistical significance of the results between the two groups within each parameter (upstream and downstream of the hydropower plant) was also checked using the two-tailed Mann–Whitney U Test (Wilcoxon rank test) [43]. For this test, we assumed a null hypothesis that the medians for the analyzed samples were identical and that the distribution of the dependent variables does not coincide with the normal distribution. The method calculates the U value in the study groups (in this case, upstream and downstream of the hydroelectric power plant) and z-ratio using the formulas listed in Table 1. The calculations were performed with a p-value of <0.01.

Table 1. The method of calculating parameters in the Mann-Whitney U Test.

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

Additionally, a correlation matrix was prepared for which the Pearson correlation coefficients between each of the tested parameters (heavy metals, average diameter of the sediment grains, reaction, and electrolytic conductivity) were calculated [44]. A correlation level higher than r = 0.70 was assumed to be significant within the analyzed results [45].

When discussing the results for the heavy metals, their potential toxicity in relation to the geochemical background adopted for Poland (geochemical method) was also calculated [46,47]. The detailed classifications of this method are presented in Table 2. The following interpretation of the results was adopted: 1st class—no need for remediation/intervention and no risk to the ecosystem; 2nd class—low need for remediation/intervention and no risk to the ecosystem; 3rd class—medium need for remediation/intervention and possible risk to the ecosystem; 4th class—remediation/intervention required and risk to the ecosystem [48,49].

Table 2. Classification of heavy metals in sediments according to the geochemical method (mg/kg).

Heavy Metal	Geochemical Background (0 class)	1st Class (No Pollution)	2nd Class (Little Pollution)	3rd Class (Medium Pollution)	4th Class (Heavy Pollution)
Cu	<6	6–19.9	20–99.9	100–199.9	≥200
Ni	<5	5–29.9	30–49.9	50–99.9	≥100
Cr	<5	5–19.9	20–99.9	100–499.9	≥500
Zn	<48	48–199.9	200–999.9	1000–999.9	≥2000
Pb	<10	10–49.9	50–199.9	200–499.9	≥500
Cd	<0.5	0.5–0.99	1–4.9	5–19.9	≥20

In addition, sediments were classified using a method developed by the Federal Environment Agency of Germany (LAWA—Lander–Arbeitsgemeinschaft Wasser), which focuses on the degree of anthropogenic interference with heavy metal contamination of sediments (Table 3) [50,51]. In this case, class 0 means no human pressure, and 5th class—a very strong influence of anthropogenic activity. The 2nd class, indicating medium pollution, is taken as a benchmark for the results obtained.

Table 3. Classification of heavy metals in sediments according to the LAWA method (mg/kg).

Heavy Metal	0 Class (no Pollution)	1st Class (Little Pollution)	2nd Class (Medium Pollution)	3rd Class (Noticeable Pollution)	4th Class (Heavy Pollution)	5th Class (Very Heavy Pollution)
Cu	≤20.0	20.1–40.0	40.1–60.0	60.1–120.0	120.1–240.0	>240.0
Ni	≤30.0	30.1–40.0	40.1–50.0	50.1–100.0	100.1–200.0	>200.0
Cr	≤80.0	80.1–90.0	90.1–100.0	100.1–200.0	200.1–400.0	>400.0
Zn	≤100.0	100.1–150.0	150.1–200.0	200.1–400.0	400.1–800.0	>800.0
Pb	≤25.0	25.1–50.0	50.1–100.0	100.1–200.0	200.1–400.0	>400.0
Cd	≤0.30	0.31–0.60	0.61–1.20	1.21–2.40	2.41–4.80	>4.80

The analyses were performed with the use of Statistica 13 (Dell, Round Rock, TX, USA), SPSS Statistics 26 (IBM, Armonk, NY, USA), and Office 2013 (Excel 2013 and Word 2013; Microsoft, Richmond, WA, USA). The map of the area was created in QGIS 2.8.4 (QGIS Development Team, Open Source Geospatial Foundation Project).

3. Results and Discussion

3.1. Grain Size Composition

The obtained results (Figure 2) indicate that the grain compositions of the sediments upstream and downstream of the hydroelectric power plants were different. In spring, at points upstream of the hydroelectric power plant, the average grain diameter of the floating parts (<2.0 mm) was between 0.018 and 0.034 mm, and in the fall, between 0.015 and 0.021 mm, which correspond to the silt fraction. Downstream of the hydroelectric power plants, the average grain diameter was between 0.094 and 0.262 mm in the spring and between 0.098 to 0.235 mm in the fall, which correspond to the sand fraction. Taking into account the results from points adjacent to the hydropower structure, the average grain diameter increased more than 12 times after passing through the hydropower plant, regardless of the season. It was noted that with increasing distance from the hydroelectric power plant, the mean grain diameter decreased (Figure 3).

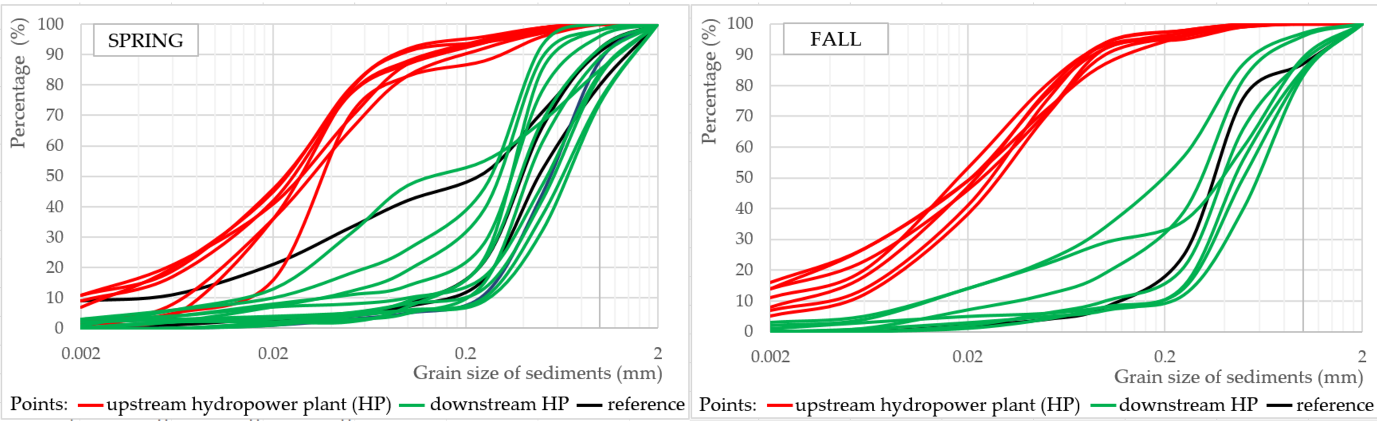

Figure 2. Percentage of the sediment fraction with different grain sizes near the hydropower plant on the Ślęza River.

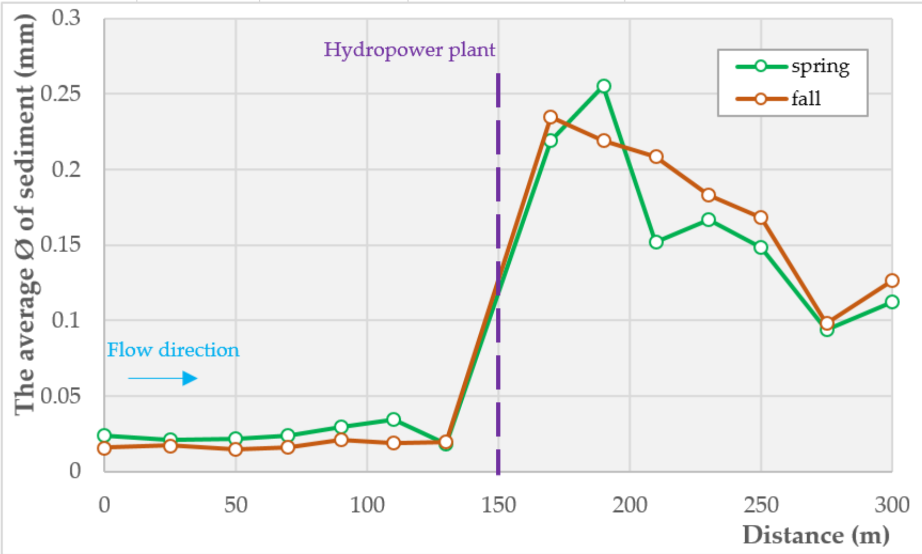

Figure 3. Average grain diameter of the tested sediments near the hydroelectric power plant on the Ślęza River.

These results are consistent with the more detailed classification in Table 4; upstream of the hydroelectric power plant, there was loamy silt and clayey silt, and downstream, there was mainly loose sand and weakly loamy sand. At the reference points, a more diversified grain size composition was noted, comprising sandy loam and loose sand. No significant differences in the results were noticed between the seasons. In the fall, clayey silt appeared at points upstream of the hydroelectric power plant more often than coarse loamy silt, while in spring, at points downstream of the hydropower plant, there was loose sand and slightly loamy sand, as well as, at one point (100 m downstream of the power plant), sandy loam (a lower content of sand fractions in the composition, and a different ratio of silt and fine particles). Upstream of the hydroelectric power plant, silt and fine particles constituted the largest share of the fine earth, usually around 50% and 40%, respectively, while downstream, the sands constituted 80–95% (Figure 4).

In regard to the fractions with a grain diameter greater than 2 mm, the occurrence of materials of both natural origin (such as pieces of branches, gravel and stones) and artificial origin (waste, elements of reinforcements of the banks and bottom of the watercourse) was noted. Upstream of the hydroelectric power plant, their content was usually nearly zero, and downstream and at the reference points, it was clearly higher (by weight, between 0 and 6, 4 and 56, and 17 and 48, respectively, assuming the fine earth fractions to be 100).

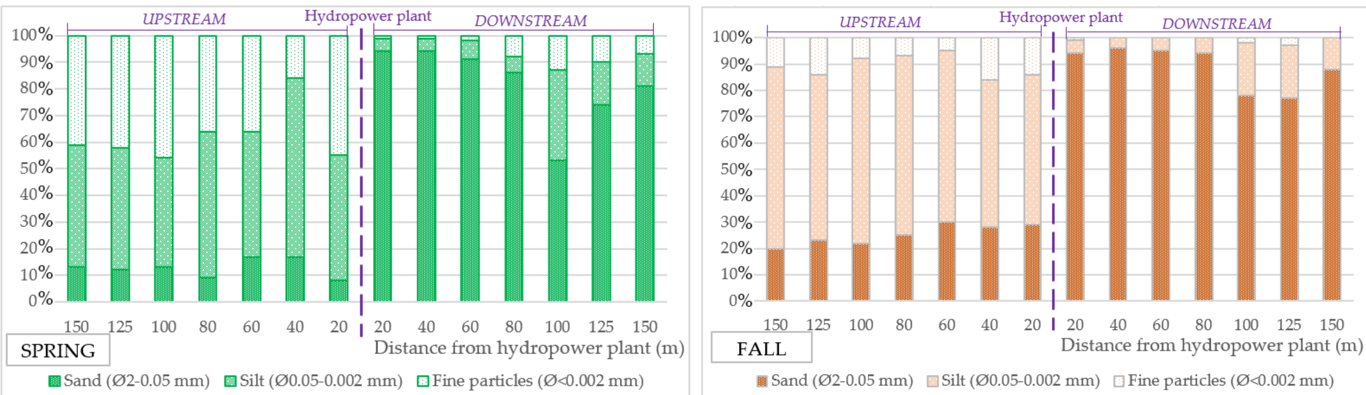

Figure 4. The percentage ratio of sand, silt, and fine particles (clay) in the investigated sediment near the hydroelectric power plant on the Ślęza River.

Table 4. Classification of the granulometric composition of sediments near the hydroelectric power plant on the Ślęza River.

Location	Distance from Hydropower Plant (m)	Granulometric Group	
		Spring	Fall
Reference	18,500	loose sand/sandy loam	loose sand
Upstream hydropower plant	150	loamy silt	loamy silt
	125	loamy silt	clayey silt
	100	loamy silt	loamy silt
	80	loamy silt	loamy silt
	60	loamy silt	loamy silt
	40	loamy silt	clayey silt
	20	loamy silt	clayey silt
Downstream hydropower plant	20	loose sand/weakly loamy sand	loose sand
	40	loose sand	loose sand
	60	loose sand	loose sand
	80	loose sand/weakly loamy sand	loose sand
	100	sandy loam	loamy sand
	125	loamy sand	loamy sand
	150	weakly loamy sand	weakly loamy sand

3.2. Heavy Metals

The concentrations of heavy metals at the examined points were varied (Table 5). In each case, they were higher upstream of the hydroelectric power plant than downstream (upstream: Zn > Cu > Ni > Pb > Cr > Cd; downstream: Zn > Cu > Cr > Ni > Pb > Cd), and at the reference points they were the lowest (Cu, Zn, Cd and Pb) or average (Ni, Cr). The differences in the concentrations of elements were significant, and in relation to the calculated medians upstream and downstream of the hydropower plant, Cu was 8.74 times higher than the median value at points upstream of the hydropower plant than downstream, Ni was 9.53 times higher, Cr was 3.63 times higher, Zn was 8.26 times higher, and Pb was 6.33 times higher.

Table 5. Basic statistical results of the heavy metal analyses in the sediment near the hydroelectric power plant on the Ślęza River.

	Upstream			Downstream			Reference		
	Min	Max	Median	Min	Max	Median	Min	Max	Median
Cu	85.74	223.09	139.44	2.79	73.09	15.96	2.60	10.52	3.43
Ni	71.36	90.71	78.36	2.59	37.52	8.22	7.67	18.92	9.11
Cr	29.64	48.54	35.88	4.15	32.30	9.90	24.46	72.29	31.63
Zn	341.00	645.52	551.27	19.73	394.57	66.72	11.84	35.21	14.65
Pb	38.00	69.19	48.10	1.1	52.74	7.60	2.73	9.04	5.84
Cd	1.05	2.10	1.37	0.00	2.64	0.00	0.00	0.52	0.00

3.2.1. Copper (Cu)

The copper content was similar at the examined points, regardless of the season (it oscillated between 2.6 and 223 mg/kg), and was clearly higher upstream than downstream of the hydroelectric power plant (values upstream: 85.7–223 mg/kg; downstream: 2.8–73.1 mg/kg) (Figure 5). Both in spring and fall, the influence of the hydroelectric partition was visible; after passing through the hydrotechnical structure, the copper content decreased from 153 mg/kg to 12.3 mg/kg in the spring and from 191 mg/kg to 11.6 mg/kg in the fall. With regard to the geochemical background, the sediments upstream of the hydroelectric power plant were moderately or heavily contaminated with copper (classes III and IV in purity, respectively), while downstream, they were unpolluted or slightly polluted (class I or II in purity). However, these values are slightly higher than the local geochemical background (6 mg/kg). The increase in copper concentrations around 100 m downstream of the hydropower plant was most likely due to the existence of a discharge structure, which is part of the local water and wastewater infrastructure. Other factors, such as industrial activities, agriculture and the impact of transport, are much less important. The same reason can be applied to the concentrations of the other heavy metals [52]. At points upstream the hydropower plant, there is an average need for bottom sediment remediation. The most common methods of heavy metal remediation include the removal of pollutants from bottom sediments by: washing, extraction, electrochemical removal, combined electrochemical extraction method, volatile pollutant evaporation and phytoremediation. They are used in situ or ex situ [53–56].

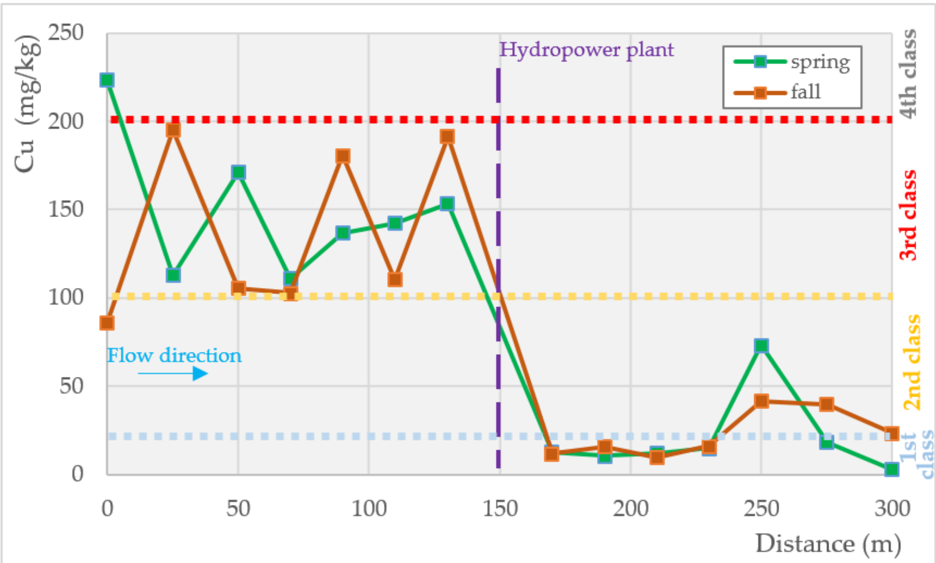

Figure 5. Changes in copper concentrations in sediments in spring and fall near the hydropower plant on the Ślęza River, along with the geochemical classification.

3.2.2. Nickel (Ni)

In the case of nickel, there is a significant difference in the results; they were higher upstream than downstream of the hydroelectric power plant and can be classified into the third purity class in relation to the geochemical criterion (moderately contaminated sediments) (Figure 6). The values at these points were similar in both seasons and ranged from 71.4 mg/kg to 90.7 mg/kg. Downstream of the hydroelectric power plants, the sediments were unpolluted (class I) or slightly polluted (class II), and nickel concentrations ranged from 2.59 mg/kg to 18.9 mg/kg (the geochemical background is 5 mg/kg). For points adjacent to the hydropower plant, the values changed from 83.8 mg/kg to 7.48 mg/kg in the spring and from 71.4 mg/kg to 6.98 mg/kg in the fall. As with copper, there is a moderate need for sediment remediation for nickel upstream from hydropower plant.

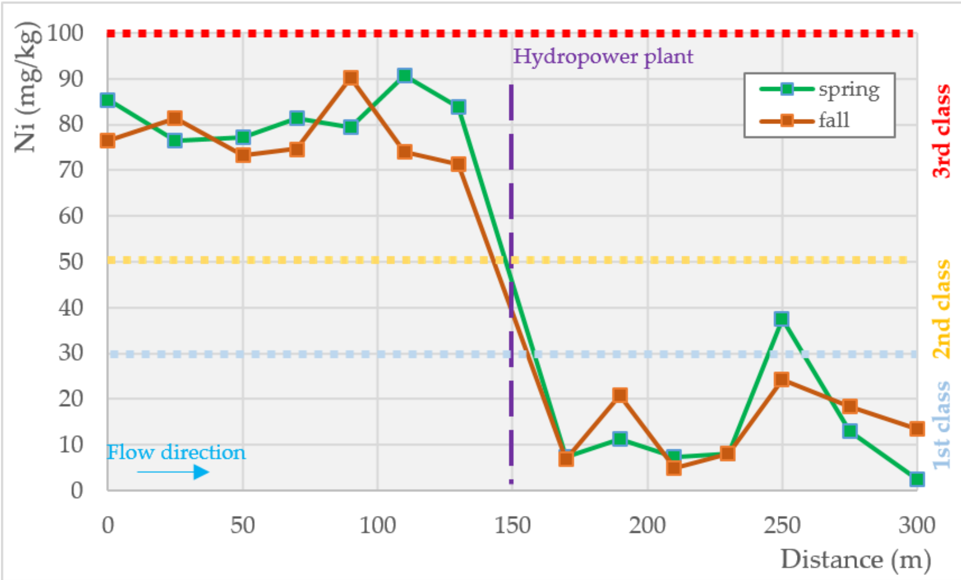

Figure 6. Changes in nickel concentrations in sediments in spring and fall near the hydropower plant on the Ślęza River, along with the geochemical classification.

3.2.3. Chromium (Cr)

With regard to the content of chromium, differences in the content of this element occurred and were higher upstream of the hydroelectric plant (Figure 7). However, the concentrations were lower and classified as class I or II in purity (uncontaminated or slightly polluted sediments). At points upstream of the hydroelectric power plant, chromium's value ranged from 29.6 to 48.5 mg/kg, and downstream, from 4.15 to 32.3 mg/kg (medians of 35.9 and 9.90 mg/kg, respectively). There were no significant differences in the values between the seasons. At the points adjacent to the hydroelectric power plant, the values in the spring were between 35.9 and 5.10 mg/kg, and in the fall, between 35.9 and 6.01 mg/kg.

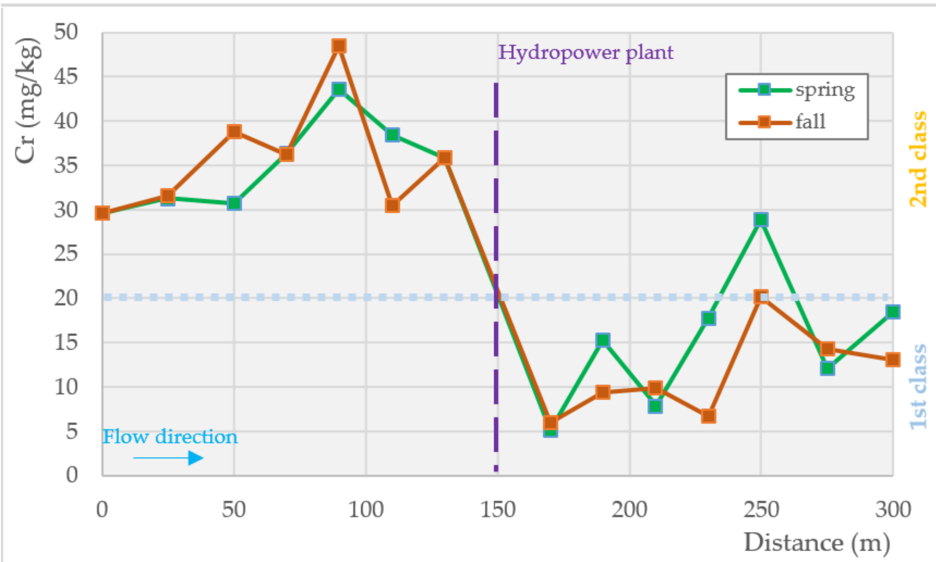

Figure 7. Changes in chromium concentrations in sediments in spring and fall near the hydropower plant on the Ślęza River, along with the geochemical classification.

3.2.4. Zinc (Zn)

The zinc content in the studied bottom sediments was low and classified as class I or II in sediment purity according to the geochemical method (no or slight contamination) (Figure 8). The concentrations of this element were higher at points upstream of the hydroelectric power plant and ranged from 341 to 652 mg/kg (median of 551 mg/kg) at these points, and downstream of the hydroelectric power plant, from 19.73 to 395 mg/kg (median of 66.7 mg/kg). After passing through the dam, the zinc concentration changed from 592 to 57.8 mg/kg in the spring and from 545 to 52.0 mg/kg in the fall.

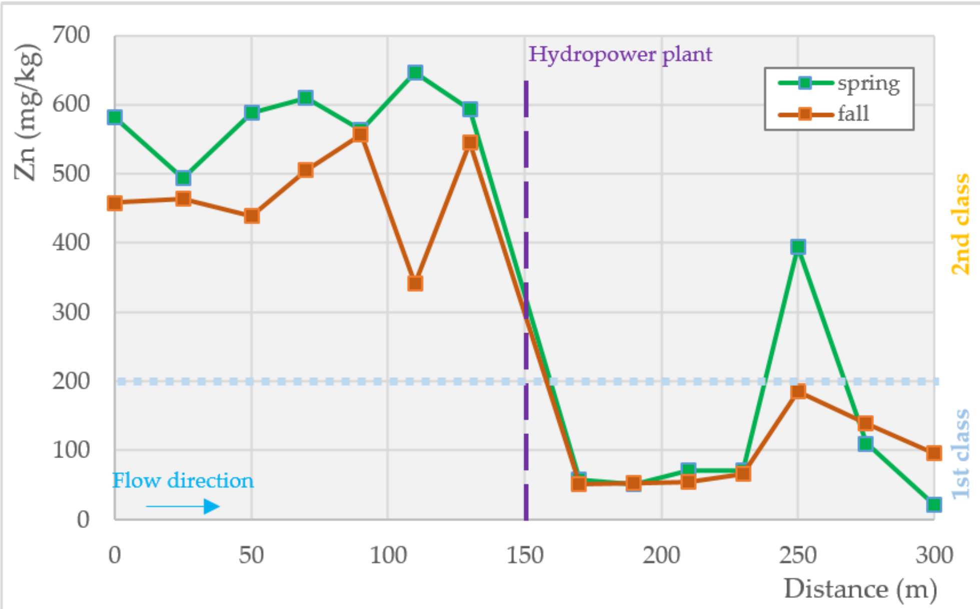

Figure 8. Changes in zinc concentrations in sediments in spring and fall near the hydropower plant on the Ślęza River, along with the geochemical classification.

3.2.5. Lead (Pb)

The results of lead concentrations in the investigated sediments indicate that its amounts were the most traceable of all the heavy metals. Most of the values were in the range of class I in purity; that is, uncontaminated sediments (Figure 9). Exceedances were only recorded at two points upstream of the hydroelectric power plant in the spring and at one point in the fall. The values were higher upstream of the hydropower plant than downstream and ranged from 38.0 to 69.2 mg/kg and from 1.1 to 52.74 mg/kg, respectively (with medians of 48.1 and 7.60 mg/kg, respectively). There were no significant differences in the concentrations between the seasons of the year. The values after passing the hydroelectric power plant changed in the spring from 47.7 to 8.33 mg/kg, and in the fall, from 69.2 to 9.00 mg/kg.

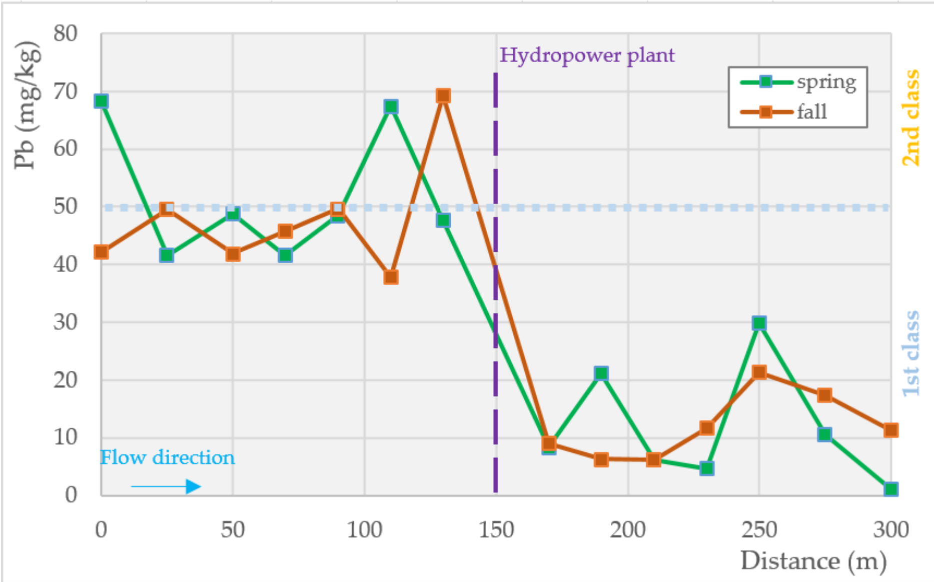

Figure 9. Changes in lead concentrations in sediments in spring and fall near the hydropower plant on the Ślęza River, along with the geochemical classification.

3.2.6. Cadmium (Cd)

The results for the sludge collected in the fall clearly show that no cadmium was found directly downstream nor up to 80 m downstream of the hydroelectric power plant (Figure 10). At further distances, traces of cadmium were observed, falling within class I of sediment purity. However, the levels of cadmium were occasionally higher than the geochemical background, which is 0.5 mg/kg). There was slightly more cadmium at the points upstream of the dam but it was a minor contamination (class II purity). The cadmium concentrations upstream of the hydropower structure ranged from 1.05 to 2.10 mg/kg, while downstream, from 0.00 to 0.80 mg/kg (with medians of 1.37 and 0.00 mg/kg, respectively). After passing through the hydroelectric power plant, the cadmium content was close to 0 mg/kg, while at the point upstream, it was 1.29 mg/kg (spring) and 2.10 mg/kg (fall).

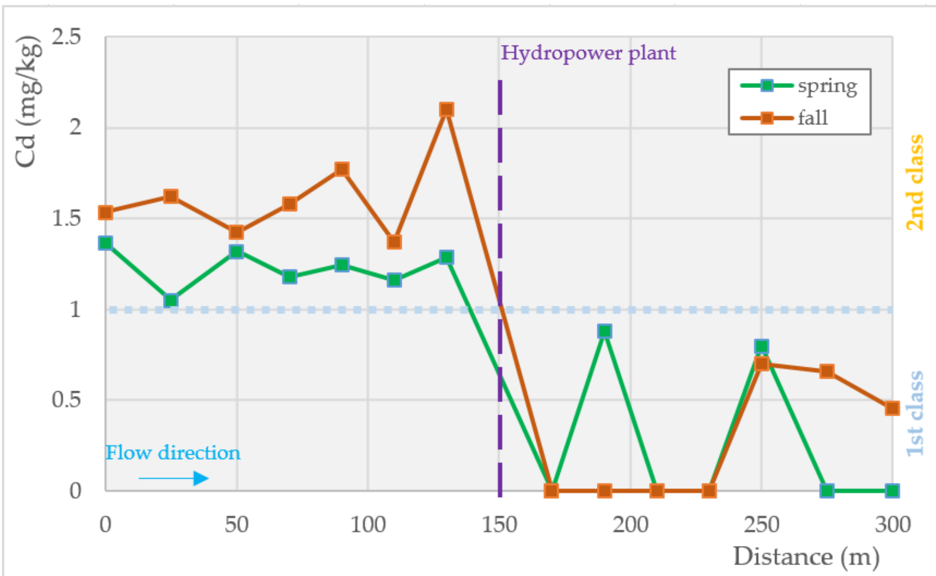

Figure 10. Changes in cadmium concentrations in sediments in spring and fall near the hydropower plant on the Ślęza River, along with the geochemical classification.

3.3. LAWA Classification of Sediment Contamination with Heavy Metals

According to the LAWA classification, the concentrations of heavy metals in the tested sediments varied—from class 0 to IV (Table 6) [50,51]. The most favourable quality was recorded at the reference point, as well as at points 20 to 80 m downstream the hydropower plant (class 0 everywhere and no anthropogenic pressures). For Ni, there were no exceedances at any point, both in spring and autumn. At points upstream, the hydroelectric power plant, the bottom sediments are more polluted, especially with copper (class III or IV, i.e., noticeable or heavy pollution), as well as chromium (class III or IV), lead and cadmium (class III). There were no significant exceedances for zinc (class I or II). A characteristic feature of the results is the higher heavy metal values 100 m downstream the hydropower plant and beyond. This is due to the existence of rainwater discharge, in accordance with the conducted field vision and available maps for this area (hydrographic, sozological). When it comes to pressures above the hydropower plant, these include in particular transport (expressway, motorway), an existing industrial plant with a production profile for water engineering, as well as general urbanization of the site (e.g., residential buildings, service areas). Due to the higher concentrations of Cu, Cd, Cr and Pb upstream the hydropower plant, remediation of the sediments is recommended.

Table 6. Classification of sediment contamination with heavy metals according to the LAWA method.

Location	Distance from Hydropower Plant (m)	Parameters						Parameters					
		Cu	**Cd**	**Ni**	**Cr**	**Zn**	**Pb**	**Cu**	**Cd**	**Ni**	**Cr**	**Zn**	**Pb**
		SPRING						***FALL***					
Reference	18,500	0	0	0	0	0	0	0	0	0	0	0	0
Upstream hydropower plant	150	IV	III	0	IV	II	III	III	III	0	IV	I	III
	125	IV	III	0	IV	I	II	IV	III	0	IV	I	III
	100	IV	III	0	IV	I	III	III	III	0	IV	I	III
	80	IV	III	0	IV	I	II	III	III	0	IV	I	III
	60	IV	III	0	IV	I	III	IV	III	0	IV	I	III
	40	IV	III	0	IV	I	II	III	III	0	III	I	III
	20	IV	III	0	IV	I	III	IV	III	0	IV	II	III
Downstream hydropower plant	20	0	0	0	0	0	0	0	0	0	0	0	0
	40	0	0	0	0	0	II	0	0	0	0	0	0
	60	0	0	0	0	0	0	0	0	0	0	0	0
	80	0	0	0	0	0	0	0	0	0	0	0	0
	100	III	I	0	III	I	II	I	0	0	II	0	II
	125	0	0	0	I	0	0	I	0	0	I	0	II
	150	0	0	0	0	0	0	I	0	0	0	0	I

3.4. pH and Electrolytic Conductivity (EC)

The values of pH and electrolytic conductivity were different at the points upstream and downstream of the hydropower plant, as well as at the reference points (Table 7). The medians for the pH at points downstream of the hydroelectric power plant were 7.47 and 7.31 in H_2O and KCl, respectively. The lowest values were upstream (7.03 and 6.79, respectively), and the highest were at the reference points (7.56 and 7.44, respectively). The conductivity value was clearly lower downstream of the hydropower plant; the median value was 113.5 µS/cm, while upstream, it was 472, and at reference points, it was 100.

Table 7. Basic statistical results of pH and EC analyzes in the sediment near the hydroelectric power plant on the Ślęza River.

Parameters	Upstream			Downstream			Reference		
	Min	Max	Median	Min	Max	Median	Min	Max	Median
pH_{H2O}	6.77	7.38	7.03	6.94	7.9	7.47	7.35	7.98	7.56
pH_{KCl}	6.47	6.9	6.79	6.88	7.68	7.31	7.08	7.75	7.435
EC (μS/cm)	204	653	472	29	275	113.5	21.3	213	99.95

The pH values for the points upstream of the hydroelectric power plant ranged from 6.77 to 7.38 (in H_2O; Figure 11) and from 6.47 to 6.90 (in KCl; Figure 12), and downstream, they ranged from 6.94 to 7.90 and from 6.88 to 7.68, respectively. The differences in the values of this parameter at points adjacent to the damming structure were equal to 0.80 and 0.88 (spring) and 0.55 and 0.74 (fall), respectively.

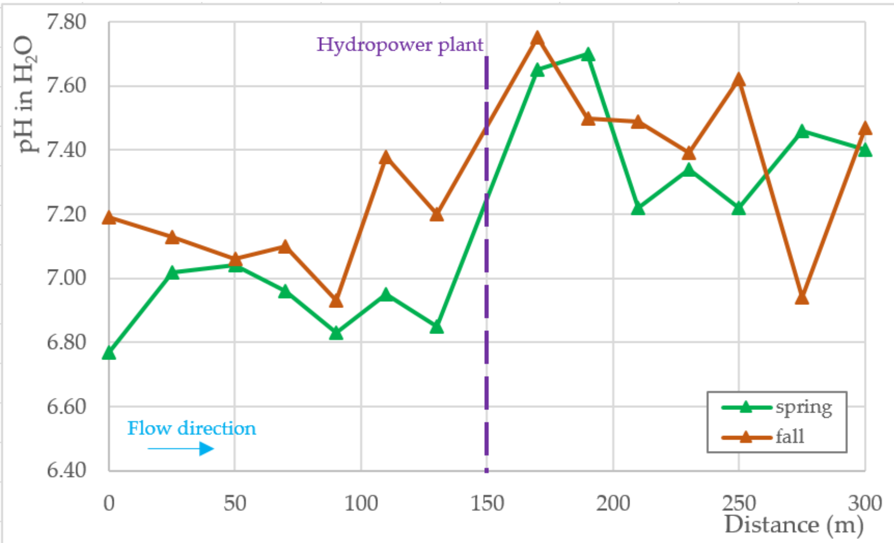

Figure 11. Changes in pH in H_2O values in sediments in spring and fall near the hydropower plant on the Ślęza River, along with the geochemical classification.

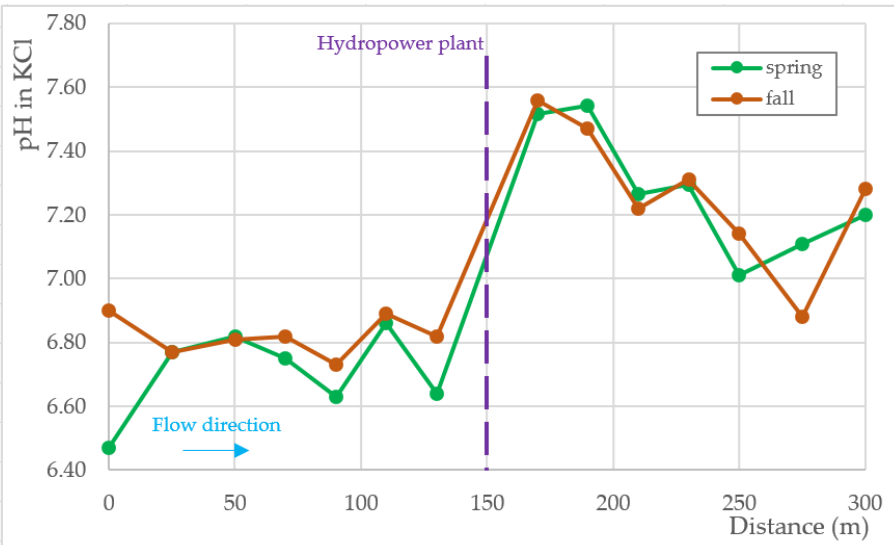

Figure 12. Changes in pH in KCl values in sediments in spring and fall near the hydropower plant on the Ślęza River, along with the geochemical classification.

With regard to conductivity, the differences in the values were more pronounced than for the pH reaction. Upstream of the hydroelectric power plant, conductivity ranged from 204 to 653 µS/cm, and downstream, from 29 to 275 µS/cm (Figure 13). After passing through the hydrotechnical structure, the conductivity values decreased, from 506 to 81.0 µS/cm in the spring and from 346 to 71.7 µS/cm in the fall.

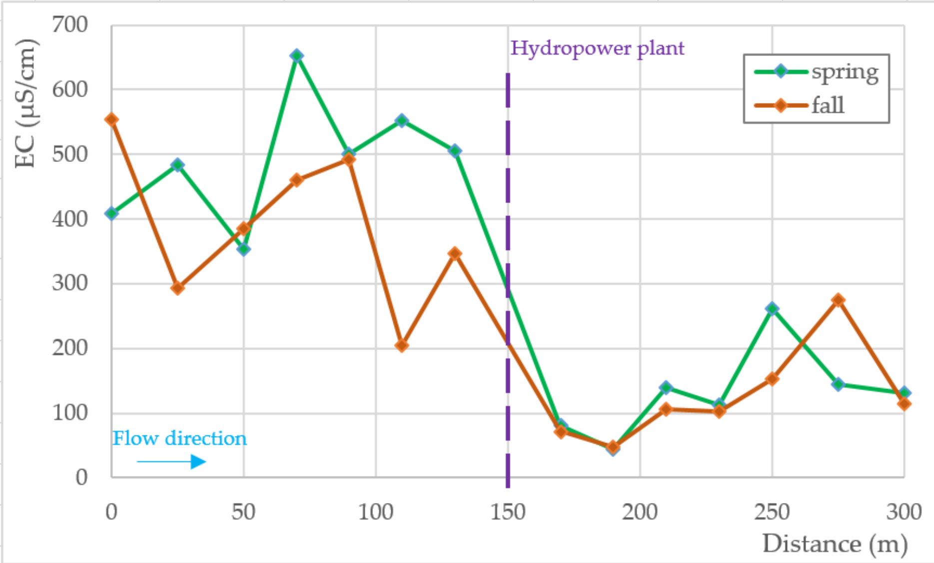

Figure 13. Changes in conductivity values in sediments in spring and fall near the hydropower plant on the Ślęza River, along with the geochemical classification.

3.5. Statistical Significance Test and Correlation Matrix between Results

The statistical analysis performed using the Wilcoxon rank test (Mann–Whitney U Test) showed that between the results at the points upstream and downstream of the hydroelectric power plants for each parameter, there was statistical significance of the U-values and z-scores for $p < 0.01$ (Table 8). This indicates that hydropower plants that act as transverse obstacles significantly affect the composition and properties of bottom sediments (heavy metals, pH, conductivity and particle size distribution).

With regard to the correlation between the studied parameters (Table 9), it was found that the results are statistically significant (for $p < 0.01$); however, the strength of the correlation was different for each of the pairs considered. The strongest relationships were demonstrated between the contents of Ni and Zn (0.972), EC and Zn (0.923), Ni and Cu, Cu and Zn (0.935), pH_{KCl} and pH_{H20} (0.095), Øav. and pH_{KCl} (0.905), and Pb and Cu (0.903). In the context of the direction of correlation, the results are consistent. There were positive correlations between the heavy metals and between the mean grain diameter and pH; they had a synergistic effect on each other. Meanwhile, between the other pairs (pH and EC, and EC and Øav.), the correlations were negative.

These dependencies are confirmed by previously performed studies, including on the Kelantan River in Malaysia [57], on the Yangtze River at the Three Gorges Dam in China [58], on the Nakdong River in South Korea [59], in dammed water reservoirs in Poland [60], in the Awetu watershed in Ethiopia [61], and in the Aar, Driedorf, and Klingenberg dam reservoirs in Germany [62].

Table 8. The results of the analysis of the Mann–Whitney test for the tested parameters of the bottom sediment near the hydropower plant on the Ślęza River.

Parameter	Upstream			Downstream			Combined			U [1]	z
	$\sum_{ranks}$	$\bar{x}_{ranks}$	U	$\sum_{ranks}$	$\bar{x}_{ranks}$	U	$\sum_{ranks}$	$\bar{x}_{ranks}$	σ		
Cu	371	26.5	0	190	10	266	561	17	27.453	0 **	−4.82643 **
Ni	371	26.5	0	190	10	266	561	17	27.453	0 **	−4.82643 **
Cr	365	26.07	6	196	10.32	260	561	17	27.453	6 **	−4.60788 **
Zn	370	26.43	1	191	10.05	265	561	17	27.453	1 **	−4.79001 **
Pb	360	25.71	11	201	10.58	255	561	17	27.453	11 **	−4.42575 **
Cd	357	25.5	14	204	10.74	252	561	17	27.453	14 **	−4.31647 **
Øav.	105	7.5	266	456	24	0	561	17	27.453	0 **	4.82643 **
pH_{H2O}	125	8.93	246	436	22.95	20	561	17	27.453	20 **	4.09791 **
pH_{KCl}	107	7.64	264	454	23.89	2	561	17	27.453	2 **	4.75358 **
EC	369	26.36	2	192	10.11	264	561	17	27.453	2 **	−4.75358 **

Designations in the table: [1] critical value of U at $p < 0.01$ is 63; ** significant at $p < 0.01$ (2-tailed).

Table 9. Correlation matrix between the studied parameters of the bottom sediment near the hydropower plant on the Ślęza River.

	Cu	Ni	Cr	Zn	Pb	Cd	Øav.	pH_{H_2O}	pH_{KCl}	EC
Cu	1									
Ni	**0.935** **	1								
Cr	0.536 **	0.629 **	1							
Zn	**0.935** **	**0.972** **	0.563 **	1						
Pb	**0.903** **	**0.888** **	0.479 **	**0.901** **	1					
Cd	**0.755** **	**0.792** **	0.634 **	**0.745** **	0.697 **	1				
Øav.	**−0.836** **	**−0.887** **	−0.606 **	**−0.868** **	**−0.746** **	−0.683 **	1			
pH_{H2O}	**−0.746** **	**−0.753** **	−0.506 **	**−0.786** **	−0.671 **	−0.571 **	**0.804** **	1		
pH_{KCl}	**−0.857** **	**−0.864** **	−0.598 **	**−0.876** **	**−0.755** **	−0.683 **	**0.905** **	**0.918** **	1	
EC	**0.788** **	**0.902** **	0.618 **	**0.923** **	**0.782** **	0.663 **	**−0.863** **	**−0.832** **	**−0.872** **	1

Designations in the table: ** correlation is significant at $p < 0.01$ (2-tailed); bold values—relevant to the analysis.

The comparison of the results of other studies indicates the convergence with the results of the studies presented in this article in terms of grain size composition, pH, electrical conductivity (Table 10) and heavy metals—Cu, Ni, Cr, Zn, Pb, Cd (Table 11). There were no changes in the pH within the Klingenberg dam in Germany [62], within Vaussaire in France—an increase of 18.9% downstream the dam [63], and within the Ślęza in Poland—an increase of 6.26%. In the case of electrical conductivity, there was a decrease downstream the dams: by 75.8% for Ślęza and by 67.1% for Klingenberg. In the context of the grain size composition, loamy silt or clayey silt were noted upstream the dams on the Ślęza, Klingenberg and Platanovrisi (Greece) [64], while downstream, loose sand or loam were noted. After passing through the dams, the sediments are more coarse than downstream.

Table 10. Comparison of the mean test results for pH, EC and particle size distribution for various research [62–64].

Reference		This Research		Hahn et al. 2018 [62]		Frémion et al. 2016 [63]		Kamidis & Sylaios 2017 [64]	
Location / Parameter		Ślęza, Poland		Klingenberg, Germany		Vaussaire, France		Platanovrisi, Greece	
		Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
pH_{H_2O}		7.03	7.47	4.50	4.50	5.30	6.30	-	-
EC (µS/cm)		472	114	550	181	-	-	-	-
Particle sizes (%)	Sand	21.0	92.0	5.1	40.6	-	-	31.5	97.5
	Silt	72.0	5.0	69.2	39.6	-	-	54.0	2.2
	Clay	7.0	3.0	25.7	20.1	-	-	14.5	0.3

Table 11. Comparison of the mean test results for heavy metals for various research [65–67].

Reference	This Research		Zhao et al. 2017 [65]		Shim et al. 2015 [66]		Aradpour et al. 2020 [67]	
Location / Parameter	Ślęza, Poland		Three Georges, China		Guam, South Korea		Sabalan, Iran	
	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
Cu	139.44	15.96	58.0	39.0	61.3	27.6	70.0	61.0
Ni	78.36	8.22	50.0	43.0	24.1	18.5	11.0	9.0
Cr	35.88	9.90	85.0	80.0	61.2	59.7	18.0	8.0
Zn	551.27	66.72	105.0	99.0	154	136	23.0	12.0
Pb	48.10	7.60	44.0	38.0	59.1	29.1	53.0	45.0
Cd	1.37	0.00	0.70	0.60	0.50	0.20	-	-

In the range of concentrations of the tested heavy metals, their decrease occurs after passing through the dam, which means that they are retained upstream these hydrotechnical structures. In this case, there is 100% coincidence with the results of other studies, i.e.,:

- Cu = decrease downstream dams by 88.6%; 32.8%; 55.0%; 12.9% (respectively: Ślęza, Poland; Three Georges, China [65]; Guam, South Korea [66]; Sabalan, Iran [67]);
- Ni = 89.5%; 14.0%; 23.2%; 18.2%;
- Cr = 72.4%; 5.88%; 2.45%; 55.6%;
- Zn = 87.9%; 5.71%; 11.7%; 47.8%;
- Pb = 84,2%; 13.6%; 50.8%; 15.1%;
- Cd = -; 14.3%; 60.0%; no data.

4. Conclusions

The results of the conducted analysis show that hydropower plants significantly affect the composition and properties of bottom sediments. Large amounts of sludge are deposited on damming weirs, accumulating heavy metals among other substances. As it has been shown, in most cases, these metals do not show any toxic properties, and their concentrations do not differ significantly from the local geochemical background. Only at one point, located upstream of the hydroelectric power plant, there was severe copper contamination. Higher concentrations of heavy metals occurred upstream of the hydropower plant, and the differences in the concentrations of elements were significant. In relation to the calculated medians upstream and downstream of the hydropower plant, Cu was 8.74 times higher median value at points upstream of the hydropower plant than downstream, Ni was 9.53 times higher, Cr was 3.63 times higher, Zn was 8.26 times higher, and Pb was 6.33 times higher.

It was also shown that the tested parameters of the sediments interacted with each other and were correlated; heavy metals showed a synergistic, positively correlated effect, while in other configurations (taking into account the reaction, conductivity, and mean diameter of the sediment grains), the effect was negative and inversely proportional. The higher content of heavy metals upstream of the hydroelectric power plant resulted from the presence of finer sediment, classified as dust, in this section. Downstream of the hydroelectric power plant, there were mainly sands, which showed a lower ability to absorb components due to the higher content of the mineral fraction.

Due to the fact that a large portion of sediments are deposited upstream of dams on rivers, the topic presented in this article is particularly important, both from an environmental point of view (large loads of components, including pollutants, deposited in sediments) and from a socio-economic point of view. In the context of fisheries, due to geomorphological changes in the riverbed associated with the transport of bottom sediments, the structure and species composition of ichthyofauna, which are the habitat, breeding place, and food base for alluvials, are rebuilt. The rational management of bottom sediments is in line with the idea of sustainable development and the goals set by the United Nations for 2030 (the so-called 2030 Agenda).

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