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Use Bottom Sediment to Agriculture—Effect on Plant and Heavy Metal Content in Soil

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Abstract: Removing bottom sediment from water reservoirs and rivers can, on the one hand, be an effective method to restore lakes, and on the other—be used for plant production, ensuring the recycling of nutrients. The aim of this research was to evaluate the possibilities of using various types of bottom sediment and its impact on heavy metal content in soil and plants. For this purpose, a pot experiment was carried out using white mustard (*Sinapis alba*) as a test plant. The total content of heavy metals (Cd, Cu, Zn, Pb) was determined in soil and plant. The addition of all types of bottom sediment increased heavy metal content in the soil. The results indicate that adding bottom sediment resulted in a significant increase in plant yield in comparison to the control. The highest yield as a result of direct effect was obtained for a combination with a 5% addition of dam sediment, while as a result of residual effect, the highest yield was achieved for a mixture with a 10% addition of pond sediment. The values of the transfer factor (TF = Cplant/Csoil) indicate a high accumulation of zinc and low accumulation of lead in the plant.

Keywords: dam sediment; pond sediment; river sediment; trace elements; mustard; soil

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1. Introduction

Sediment is an integral part of aquatic environments. Lying at the bottom of water reservoirs, it collects organic particles and mineral parts of various sizes. All water reservoirs and rivers silt up over time, but excessive accumulation of bottom sediment reduces their capacity and depth. For this reason, dredging and removing accumulated bottom sediment is regularly carried out for rivers and water reservoirs (both natural and artificial) [1,2]. Dredging is the basic solution to help combat the problem of excessive siltation. In a short period of time, it generates a large amount of sediment that has to be handled so as not to pose a threat to the environment and living organisms. Continuous dredging of waters such as rivers, lakes, ports, and other semi-enclosed water bodies produces millions of tons of dredged sediments around the world. Europe-wide, the volume of dredged material is estimated at 200 m^3 per year [3–5]. Bottom sediment is an important element of water bodies. The sediment is a product of the processes occurring directly in the aquatic environment, as well as in the whole catchment area. Sediment dredged from water bodies is generally fine-grained or extremely fine-grained, mostly formed fine sand, silt, and clay minerals. However, by considering type of dredging activities and the diversity of the dredged environments, it can be stated that sediment will be characterized by different physico-chemical properties, microbial communities, and pollutant types and loads. The physico-chemical properties of bottom sediment depend on a number of natural and anthropogenic factors. Sediment from the natural environment may be rich in debris and vegetation, sediment from industrial areas may be contaminated by heavy metals (Cd, Hg, As, Zn) and organic pollutants (PAHs—Polycyclic Aromatic Hydrocarbons, PCBs—Polychlorinated Biphenyls), sediment from agricultural areas may contain high levels of biogenic elements in particular nitrogen and phosphorus and potassium, calcium, as well as magnesium, and agrochemicals, and sediment of urban areas may contain mud, boulders, construction debris, and solid waste [5–10].

Defining the composition, as well as the physical and chemical properties of the dredged sediment is an essential step towards identifying the future route of sediment [11,12]. In scientific literature, there are many studies showing that dredged sediment can be used as a raw material for the development of different materials in construction, the manufacture of concrete, the construction of roads or production of bricks [4,13–16]. However, the cheapest way to process it is to use it for agricultural purposes. Due to its physicochemical properties, bottom sediment may be used as a fertilizer in the future. Such a management method is in line with the principles of a circular economy and the European Green Deal. The possibilities of agricultural use of dredged sediment are mainly connected to a high organic matter content, neutral or alkaline reaction, an appropriate content of available forms of phosphorus, potassium, and magnesium, which prove their fertility. However, little reports in the scientific literature concerns the possibility of agricultural use of bottom sediment on sandy, poor soils [17–19].

On the other hand, bottom sediment is characterized by tremendous variability, both in terms of its physical [20,21] and chemical composition [8,19], including the presence of heavy metals, which poses a potential obstacle to its application in agriculture [22]. The most common metals found in sediment are those frequently used in industry, such as zinc, copper, chromium, cadmium, lead, nickel [19]. The heavy metal contamination in the sediment is a significant environmental problem. It is toxicity, non-degradability, and high bioaccumulation potential in biota and the food chain [23]. Boszke et al. [24] indicate that bottom sediment from large rivers is exposed to pollution by anthropogenic emissions, especially mercury, cadmium, and zinc. Lychagin et al. [25] showed that the impact of anthropogenic emissions on such a large river is relatively low, and the content of heavy metals in the bottom sediment was low and fell within the accepted standards. Moreover, Martínez-Santos et al. [26] showed that Zn, Cu, and Cr come mainly from anthropogenic sources. At the same time, they pointed out that the chemical composition of the bottom sediment depends on the content of organic matter, which binds specifically with Cu and Cr. Zn was evenly distributed in all other tested fractions.

Bottom sediments from reservoirs with dams are characterized by a different metal accumulation dynamic. The water flow is severely restricted. There are also no flood waves that contribute to the long-range transport of bottom sediment. Bazrafshan et al. [27] showed that content of heavy metals in sediment did not exceed WHO guidelines. The exception was cadmium, which showed increased contents. Heavy metal concentrations in sediment decrease in the sequence Fe > Mn > Zn > Ni > Pb > Cr > Cd > Cu. Deng et al. [28], when examining bottom sediment in reservoirs with water intended for irrigation and drinking water, found that both reservoirs tested were heavily contaminated by heavy metals. The norms exceeded the greatest extent for Hg and Cd. At the same time, the authors determined that the sources of pollution came from fuel blends, industrial mills, agricultural activities, mines, and quarries. Akin et al. [29] showed statistically significant differences, especially in the content of Cd, Zn, and Pb between the seasons (spring, summer, autumn). Moreover, they found that the sediment was characterized by increased levels of arsenic and lead. Ziemińska-Stolarska et al. [30] showed that highest amounts of biogenic components were deposited in sediment of deep parts in slow-flowing waters, in stagnation zones, areas adjacent to arable land, and the sites where fine-size fractions prevailed in the deposited material. Authors showed that bottom sediment was not toxicologically contaminated in terms of cadmium, lead, and chromium content. Due to the high content of organic matter, and especially accumulated macro nutrients, bottom sediment should be used to fertilize plants. Dushyantha et al. [31] suggested that the lake sediment could possibly be used as a low-grade phosphate fertilizer for direct applications in low intensity farming. Braga et al. [32] found that bottom sediment was suitable for fertilizing agricultural land while reducing fertilization costs. Compared to conventional fertilization, using sediment 29% of costs could be saved, whereas when using sediment with low nutrient content costs were 6% higher. Bottom sediment is a good organic fertilizer if the nitrogen content is above 1.5 g kg^{-1} [32]. Furthermore, Capra et al. [33] recommended the use of bottom sediment for fertilization.

Many methods have been used for the assessment of bottom sediment heavy metals pollution and to determine the potential risk of heavy metal contamination [34]. In our research, we used the pot experiment method. The most appropriate methods to understand plant responses to the effects of various factors are field experiments. However, studying interactions and responses of plants in the field is difficult due to the complexity of factors affecting such relationship [35]. As a complement to in situ studies, pot experiments allow direct measurements under controlled conditions without the influence of distracting biotic and abiotic factors [36].

The aim of the research was to evaluate the possibilities to use various types of bottom sediment in agriculture and its impact on heavy metal content in soil and plants.

2. Materials and Methods

2.1. Site Characteristics and Experimental Designs

The pot experiment was carried out in 2018–2019 at the Experimental Station of Warsaw University of Life Sciences, located in Skierniewice (51°57′52.9″ N 20°10′05.5′ E). The pots used for research had a capacity of 10 kg of dry soil matter. The soil was collected from the Experimental Station SGGW in Skierniewice. The territory is not under the anthropogenic impact. The soil was taken with a spade from a depth of 0–20 cm. After drying to air-dry condition, the soil was ground and then sieved through a sieve with a diameter of 2 mm, and then thoroughly mixed. Haplic Luvisol was used, with a granulometric composition of slightly loamy sand, to which bottom sediment was added from the Vistula (river) (collection site—Warsaw, 52°12′38.16″ N 21°5′35.879″ E), the Łupia River (dam) (collection site—Skierniewice, 51°51′50.868″ N 20°07′32.102″ E), and a fishpond (pond) (Agricultural Experimental Station in Żelazna, 51°51′838″ N 20°07′176″ E) (Figure 1).

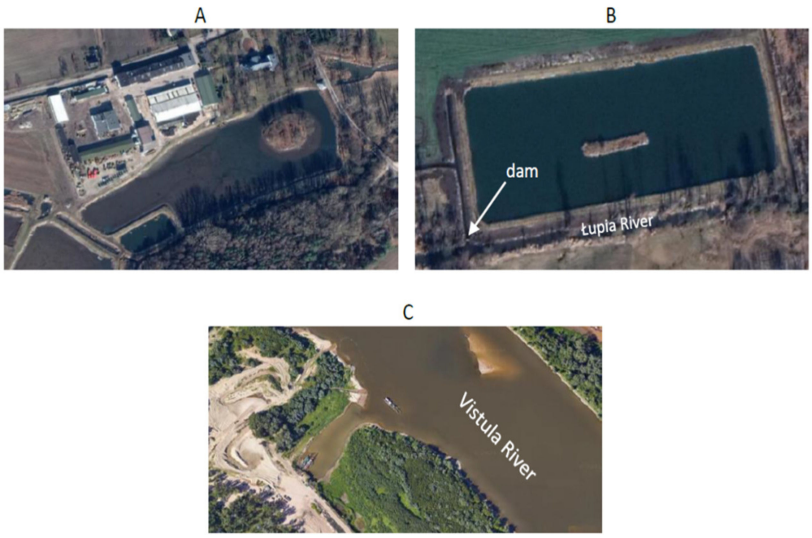

Figure 1. Place of collection of bottom sediment: **A**—pond, **B**—dam, **C**—Vistula River [Own study based on Google Maps].

The bottom sediment from Warsaw was collected from where it had been dumped after being dredged from the Vistula and separated from the sand. Bottom sediment was also collected from a carp farming pond with a total area of 0.73 ha and a depth of 0.8–1.4 m. The bottom sediment from the Łupia River was collected at the 1.5 m-high dam constructed to control water flow to breeding ponds. From each point five samples were taken. Then a bulk sample was created. The top 0–20 cm depth of sediment samples was collected using an Ekman sampler and carried within zip-mouthed PVC packages. Bottom sediment samples were air dried at room temperature and sieved through a 2 mm nylon sieve to remove coarse debris. The grain size fractions were determined according to the Cassagrande aerometric method modified by Prószynski [37]. The sand (0.05–2.0 mm), silt (0.002–0.05 mm), and clay (<0.002 mm) fractions were determined. Bottom sediment was added only once in 2018 in the following doses: 1%, 5%, 10%, and 20% of the total weight of the soil. Selected physicochemical properties of bottom sediments are presented in Table 2 The selected sediment was mixed throughout the soil. The control was an object without the application of bottom sediment (Table 1). No mineral fertilization was used in the experiment. The experiment was conducted in 3 replications. The test plant was white mustard *Sinapis alba* (the Warta variety). Mustard was selected to evaluate the effects of heavy metals on plants because plants from the family Brassicaceae, which are considered to be tolerant to excessive quantities of heavy metals in substratum, although their tolerance to particular metals varies. Additionally, mustard is easy to harvest and produce considerable amount of biomass in a short time. The mustard was sown in the first year on 9 May 2018, and in the second year on 3 May 2019. After the emergence, 15 plants were left in each pot. During plant vegetation, pots were watered with distilled water to 60% water holding capacity (WHC) of the soil. Mustard plants in both years were harvested at the same time BBCH 65 (full flowering 50% of flowers open). The plants were cut at full flowering (BBCH 65).

Table 1. Scheme of the experiment and amounts of heavy metals introduced to soil with bottom sediment (mg per pot).

Bottom Sediment	Dose of Bottom Sediment (%) *	Cd	Cu	Zn	Pb
River	1	0.03	0.15	3.47	0.29
	5	0.16	0.78	17.36	1.48
	10	0.33	1.56	34.73	2.97
	20	0.66	3.12	69.46	5.94
Dam	1	0.04	0.39	1.25	0.81
	5	0.22	1.99	6.25	4.04
	10	0.45	3.98	12.51	8.08
	20	0.90	7.96	25.02	16.16
Pond	1	0.03	0.74	2.74	1.26
	5	0.18	3.71	13.72	6.31
	10	0.37	7.42	27.45	12.61
	20	0.74	14.84	54.90	25.22
Control	-	-	-	-	-

* % of the total dry matter of the soil in pot.

Plants after harvest were washed in distilled water.

2.2. Measured Parameters

Soil samples were collected after mustard harvesting. The soil samples were air dried and sieved to <2 mm. The soil and sediment samples were analyzed for pH by the potentiometric method after extraction with 1 mol·dm^{-3} KCl [38], for total carbon (C_{org}) and total nitrogen (N_{tot}) using Vario Max analyzer (Elementar, Langenselbold, Germany), as well as for total forms of heavy metals after the decomposition by aqua regia using ICP (inductively coupled plasma) method (IRYS Advantage ThermoElementar, Cambridge, UK) [39]. We used the Certified Reference Material CRM no. LGC 6187 for River sediment for metal determination. The available forms of phosphorus and potassium using the Egner-RiehmDL method were determined in soil and the total forms of P and K using ICP method were determined in bottom sediment [40].

Table 2. Soil and bottom sediment properties.

Properties	Unit	Soil	Bottom Sediment		
			River	Dam	Pond
Sand * (0.05–2.0 mm)	%	72	90	86	65
Silt * (0.002–0.05 mm)		21	6	10	28
Clay * (<0.002 mm)		7	4	4	7
pH	-	5.21	7.62	6.60	6.37
C_{org}	$g \cdot kg^{-1}$	7.20	2.70	4.40	15.60
N_{tot}		0.70	0.30	0.40	1.40
Ca		0.65	5.28	4.38	3.47
Mg		0.04	1.93	1.21	0.71
P_{ER} **	$mg \cdot kg^{-1}$	39.21	2.27	21.05	32.63
K_{ER} **		72.11	230.02	350.92	2095.43
Cd		0.21	0.33	0.45	0.37
Cu		2.22	1.56	3.98	7.42
Zn		9.44	34.73	12.51	27.45
Pb		9.49	2.97	8.08	12.61

* According to PTG (Soil Science Society of Poland) classification [41]; ** P and K content Egner-Riehm method.

After harvest plants were dried at 105 °C and then ground in a Retsh mill at 5000 rpm. Heavy metals content in plants material were determined using ICP method (IRYS Advantage ThermoElementar, Cambridge, UK) after wet mineralization in a closed system in a microwave (ETHOS UP, Milestone INC, USA) (10 cm^3 of a mixture of concentrated acids HNO_3 and $HclO_4$ was added to 0.3 g of plant material in a ratio of 5:2 and mineralized for a period of 0.5 h).

The transfer factors (TF) of heavy metals from soil to plants were calculated using the following equation (1) [42–44]:

$$TF = Cplant/Csoil \quad (1)$$

where Cplant is heavy metal concentration ($mg \cdot kg^{-1}$ FW) and Csoil is heavy metal concentration ($mg \cdot kg^{-1}$ DW) in the soil that was used for growing the plants. TF values ≥1 indicate higher absorption of metal from soil by the plant and higher suitability of the plant for phyto-extraction and phytoremediation. Values lover than 1 indicate lower metal absorption [42–44].

2.3. Statistical Analysis

For the assessment of the influence of bottom sediment on the content of heavy metals in soil and in plants, and the value of the TF coefficient, statistical analysis was performed by using multi-way analysis of variance (ANOVA) at a significance level $p \leq 0.05$ with the use of Statistic aver. 13.3 software (TIBCO, Software INC., Palo Alto, CA, USA). Figures 2 and 3 show the mean values from three replications. Error bars mean standard deviation (±SD).

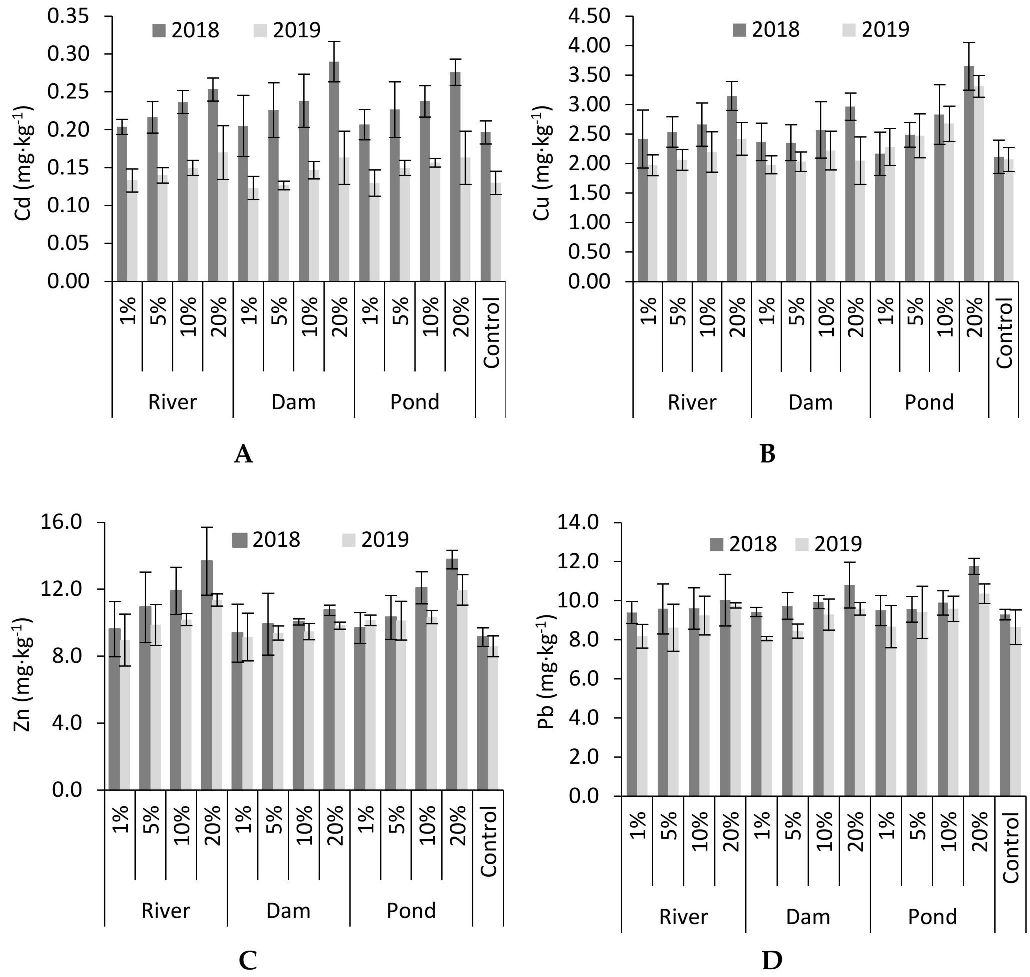

Figure 2. The effect of bottom sediment on total forms of **A**—cadmium, **B**—copper, **C**—zinc, **D**—lead in soil. 1%, 5%, 10%, 20%—doses of bottom sediment; control—without bottom sediment application.

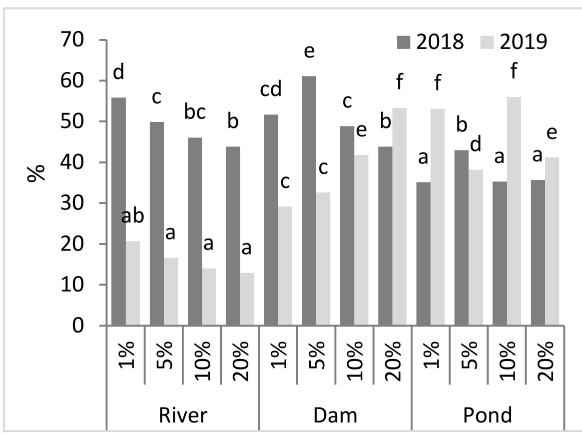

Figure 3. Yield increase in relation to the control object due to the use of bottom sediment.

3. Results

3.1. Characteristics of Bottom Sediment

Depending on the collection site, the bottom sediment analyzed differed in terms of its physical and chemical properties, such as texture, pH value, content of organic matter and macronutrients, and content of heavy metals. The highest content of sand was found in the sediment from the Vistula, while the lowest occurred in the bottom sediment from the pond

(Table 2). In terms of the content of clay, all types of sediment were similar. The sediment from the pond contained the highest content of silt, which was almost five times greater compared to the sediment from the Vistula and three times greater than in the sediment from the dam. The sediment from the Vistula River had the highest pH value. The bottom sediment from the dam and the pond were similar in terms of pH. Significant differences were found in terms of the organic carbon content, which was the highest for the sediment from the pond and the lowest (almost seven times lower) for the sediment from the Vistula. The sediment differed significantly in terms of the content of macronutrients. The highest content of nitrogen, phosphorus, and potassium was found in the sediment from the pond, and the lowest in the sediment from the Vistula (Table 2). In terms of heavy metal content, the highest values were recorded for Zn and the lowest for Cd. The sediment from the Vistula River contained the lowest amounts of metals (except for Zn), while the sediment from the pond contained the highest (except for Cd).

3.2. The Effect of Bottom Sediment on Heavy Metals Content in Soil

The bottom sediment application increased the content of heavy metals in soil. Both the type of bottom sediment and the dose were factors influencing the content of the tested heavy metals in the soil. Usually, the metal content in the soil increased with the dredged sediment dose, however research showed that the factor that had the greatest impact on the content of the tested metals in the soil was the sediment type. The addition of bottom sediment to the soil resulted in an increase in the metal content in the soil compared to the control (Figure 2).

In the first year, the average increase in the content of Cu in the soil was 27% for the sediment from the Vistula, 31% for the dam sediment, and 33% for the pond sediment, as compared to the control. For Cd, the changes were slightly lower: 15%, 22%, and 20%, respectively, and for Zn 26%, 10%, and 25%. The lowest increase was recorded for the content of Pb: 4%, 7%, and 10%, respectively. In the second year of the study, the content of the analyzed elements decreased in comparison with 2018. However, a similar trend as in the previous year of changes in the content of heavy metals in the soil was observed. However, the dynamics of changes in content were different for different types of sediment. In both years of research, the content of all heavy metals in the soil increased with the dose of bottom sediment. The highest increase in the content under the influence of the applied doses was found in the case of Cu, especially in the pond sediment, and the lowest in the case of Pb.

3.3. The Effect of Bottom Sediment on Yield and Heavy Metals Content in Plant

All the tested sediment led to an increase in the yield of plants as compared to the control. (Figure 3). In the first year of research, doses of 1% and 5% of bottom sediment had the greatest effect on the yield. In the second year, the highest increase in the yield in relation to the control was observed at the dose of 1% for sediment from Vistula river, 10% from pond sediment, and 20% form dam sediment.

Changes in heavy metal content in the soil were reflected in the concentration of these elements in the plant (Figure 4). The bottom sediment application increased the concentration of Cd, Zn, and Pb in the plant biomass in relation to the control object (Figure 4). In the first year of research, the highest concentration of analyzed heavy metals in the plant was found under the river sediment application, and the lowest in the case of dam sediment. The concentration of heavy metals in the plant varied depending on the type and dose of bottom sediment. In the case of Cd and Zn, a decrease of their concentration in the plants was usually observed with an increase in the dose of the tested sediment. In the case of Pb, a decrease in the concentration of this element was observed with an increase in the dose of sediment from the Vistula River and the dam. On the other hand, with the increase of the pond sediment dose, the lead concentration in the plant biomass increased. Only in the case of copper there was no found effect of the bottom sediment's application on the Cu concentration in the plant biomass. In both years of research, the lowest content of the tested metals was found in plants grown under the conditions of dam sediment application. In the second year of the research, there was a significant decrease in the content of the examined elements compared to the first year. The average decrease in the content of Cu in the plants ranged between 70–80%, 50–75% for Cd and 30–75% for Zn.

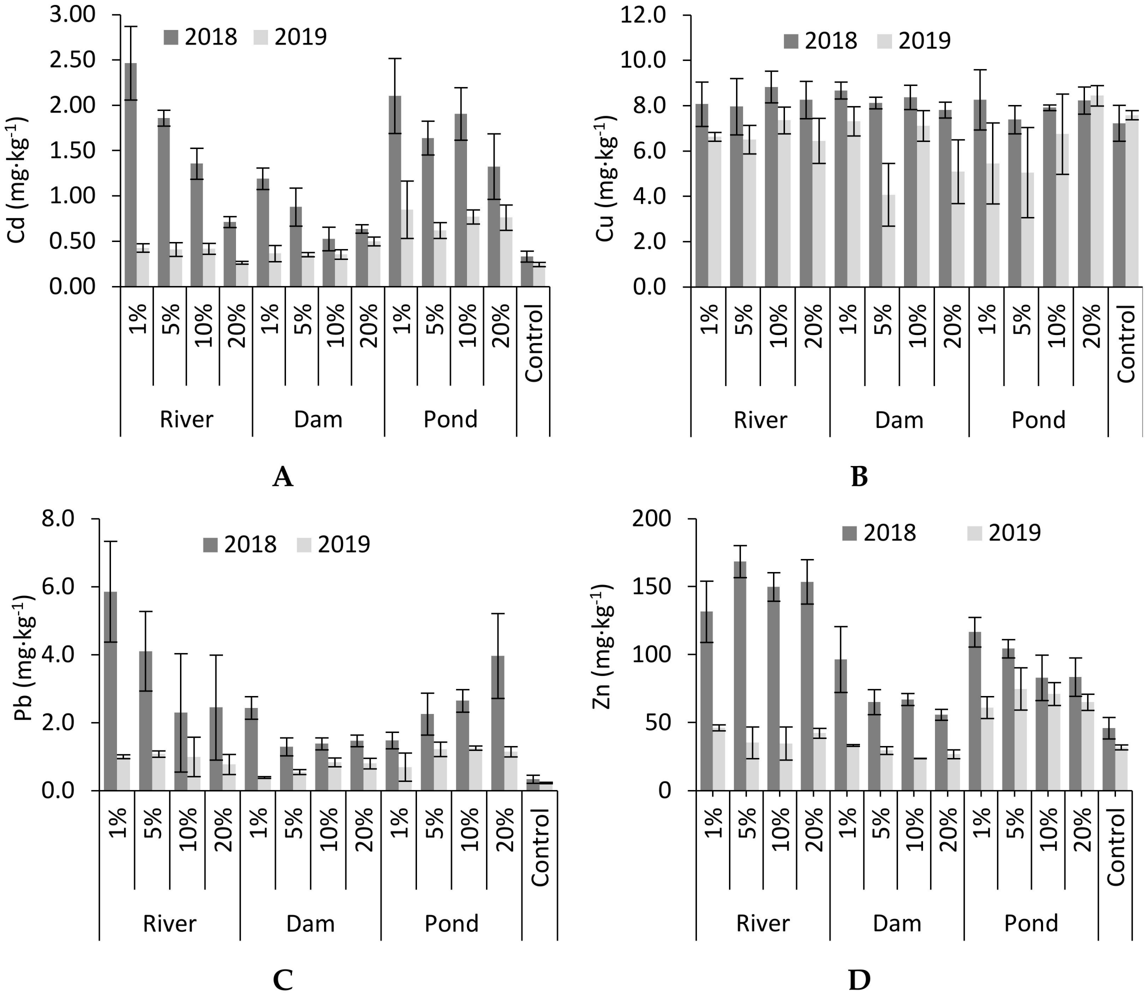

Figure 4. Heavy metals **A**—cadmium, **B**—copper, **C**—lead, **D**—zinc concentration in plant.

The changes in the content of the examined metals in the soil and plants under the influence of various types of bottom sediment were reflected in the TF, which shows the potential of a given element to be transferred from soil to plant (Table 3). The value of this factor for all elements usually was lower than 1. Higher values represent greater transfer of a given element from soil to plant. The highest values were achieved in the first year of the research, in particular for Cd. Slightly lower values were recorded for zinc and copper while the lowest were for Pb. The mean TF value for Zn is the highest among those four metals. It is over 31 times higher than TF value of Pb, 1.5 times higher than TF value of Cu and 1.1 times higher than TF of Cd. As the highest TF value, it indicates that Zn is more mobile than other metals. The mean value of transfer factor was in the descending order of Pb < Cu < Cd < Zn. These results also allow to conclude that Pb accumulation in white mustard plants is relatively low.

Table 3. Transfer factor (TF) of metals from soils to mustard plants.

Bottom Sediment	Dose of Bottom Sediment (%)	Cd		Cu		Zn		Pb	
		2018	2019	2018	2019	2018	2019	2018	2019
River	1	1.68d	0.63c	0.55a	0.55b	1.37d	1.08b	0.07c	0.02b
	5	1.21c	0.46a	0.53a	0.51b	1.13b	0.88a	0.05b	0.02b
	10	0.84b	0.55b	0.57b	0.55b	1.18c	0.91a	0.03a	0.02b
	20	0.40a	0.51b	0.51a	0.37a	0.73a	0.84a	0.03a	0.01a
	mean	1.03C	0.54B	0.54B	0.50B	1.10C	0.93D	0.04D	0.02C
Dam	1	1.81c	0.29b	0.55c	0.41b	0.57c	0.65c	0.03c	0.01a
	5	0.56b	0.27a	0.45b	0.33a	0.46a	0.43b	0.01a	0.01a
	10	0.31a	0.25a	0.43b	0.41b	0.54b	0.44b	0.02b	0.01a
	20	0.34a	0.24c	0.37a	0.46c	0.59c	0.35a	0.02b	0.01a
	mean	0.51B	0.26A	0.45A	0.40A	0.54A	0.47B	0.02B	0.01B
Pond	1	1.23c	0.36c	0.58c	0.62c	0.78c	0.91d	0.02a	0.01a
	5	1.06b	0.30b	0.52b	0.32a	0.68b	0.53c	0.03b	0.02b
	10	0.97b	0.27b	0.50b	0.52b	0.51a	0.38a	0.03b	0.02b
	20	0.73a	0.16a	0.42a	0.32a	0.48a	0.43b	0.04c	0.02b
	mean	0.99D	0.27A	0.51B	0.44A	0.61B	0.56C	0.03C	0.02C
Control		0.32A	0.31A	0.65C	0.79C	0.97C	0.20A	0.008A	0.006A

a, **b**, **c**, **d**—means for doses followed by the same letter are not significantly different from one another based on Tukey's test at $p \leq 0.05$; **A**, **B**, **C**, **D**—means for bottom sediment followed by the same letter are not significantly different from one another based on Tukey's test at $p \leq 0.05$.

The speed at which these elements transferred was the fastest for the Vistula sediment, and the slowest for the dam sediment. In the second year, the TF values were significantly lower compared to the first year. As the bottom sediment dose increased, a decrease in the TF value was observed.

4. Discussion

The analyzed sediment differed in its physical properties and chemical composition (Table 2). The properties of bottom sediment are influenced by a number of environmental and anthropogenic factors. The chemical composition of the sediment depends on the type of soils in the catchment area and their agricultural use, as well as the type of industry present in the area [45]. Augustyniak et al. [46] showed that the main factor which differentiated the sediment of the analyzed Polish lakes is its hydrological regime. One of the analyzed parameters was pH, which changed from 6.6 and 7.62 depending on the kind of the bottom sediment. As the research by Vácha et al. [6] and Fonseca et al. [47] suggests, depending on the place of origin, bottom sediment differed significantly in terms of its pH. The main chemical components of the polish lake sediment are silica, organic matter, and calcium together with carbonates [46], which may affect the neutral and alkaline reaction of bottom sediment.

Another key factor for the mobility of heavy metals in the soil is the content of organic carbon and the examined bottom sediment differed significantly in this regard. The lowest content of organic carbon (2.70 g·kg^{-1}) was recorded for the sediment from the Vistula and the highest was recorded for the pond sediment (15.60 g·kg^{-1}). The bottom sediment collected from the Vistula River contained less organic carbon than the sediment from the pond and dam. This is the result of intensive mineralization process. The bottom sediment of small rivers with low flow rates and closed and semi-open reservoirs with aqueous plant growing are richer in organic carbon [48]. Sandy sediment usually contains less organic matter than sediment with a higher silt and clay content [49]. Baran et al. [19] found that the carbon content in bottom sediment from Rzeszow Reservoir was higher, at 23.5 g·kg^{-1} of DM, but sediment from a smaller water reservoir in Narożniki has a low as 4.80 g·kg^{-1} of DM [9]. The analyzed bottom sediment differed significantly in terms of the content of macronutrients. The highest content of nitrogen, phosphorus, and potassium was found in the sediment from the pond, and the lowest in the sediment from the Vistula. Accumulation for biogenic substances in the bottom sediment depends on the environmental conditions, the morphology, and hydrology of the tank (flow fluctuations and constant water level). However, the greatest amount of nutrients is accumulated in bottom sediment in the deepest parts of the water reservoir, in stagnant water areas adjacent to agricultural land and places where fine-grained fractions predominate in the composition of the deposited material [10,50]. The content of heavy metals is often a key factor that prevents the use of sediment in agriculture [34,51–53]. The studied bottom sediment differed in the content of heavy metals. The greatest amounts of cadmium were found in the sediment from the dam, copper and Pb in the sediment from the pond, and Zn in the sediment from the Vistula River. Regardless of the origin of the bottom sediment, the content of heavy metals in it was as follows: Zn > Pb > Cu > Cd. In this research the content of heavy metals in bottom sediment depended on the place of origin. Vácha et al. [6] found a strong variability in terms of the content of the examined metals for different types of bottom sediment. A similar observation was made by Xiao et al. [54] and Shen et al. [55]. The content of heavy metals in bottom sediment depends on hydrodynamic conditions, and in river sediment is usually lower than in the water reservoirs supplied by the rivers [34,52]. The accumulation of trace elements in bottom sediment occurs along with complex physical and chemical processes, which depend on the properties of the sediment, as well as on the properties of the absorbed elements. The accumulation occurs through interaction with the solid phase, following the mechanisms of ion exchange and complex formation with humic acids, adsorption by Fe and Mn hydroxides, etc. Therefore, the accumulation and distribution of trace elements is influenced by different physical and chemical characteristics of the sediment, such as texture, particularly the content of silt and clay fraction, the content of organic carbon, carbonates, water-soluble salts, and amorphous oxides [51].

Thevenon et al. [56], Skwierawski and Sidoruk [22] and Kedir et al. [57] showed the correlation between the bottom sediment fraction and heavy metal content. If the sediment contains more fine fractions, the content of accumulated heavy metals tends to increase. As shown in Figure 2, the content of heavy metals in soil increased in condition of bottom sediment application. Research of many authors has shown that under the conditions of the application of bottom sediment, the content of heavy metals in agricultural soils increases or decreases depending on the geochemical properties of the sediment, the physico-chemical properties of the soil, weather conditions, cultivated plants. Baran et al. [19] and Tarnawski et al. [18] showed that along with an increase in the dose of bottom sediment, the content of Zn and Cu in the light, sandy soil increased significantly, while the content of Pb and Cd decreased. This relationship was confirmed by Zhao et al. [58] and Abou El-Anwar [53], who showed that all examined metals accumulate in the soil as a result of the addition of bottom sediment. Metals deposited in the bottom sediment are not bonded permanently and therefore can be released into environment if conditions change (e.g., pH or redox potential) or in the presence of organic chelates. Transport of metals in bottom sediment to soil depends on many factors resulting from the nature of both sediment and metals. The following properties of metals have an influence on their transport in the sediment: ionic charge, ionic radius, ion complexing power, oxidation state, hydration state. The bonding of metals in the bottom sediment is a reversible process, and its speed depends on pH, the type and content of organic matter and colloids, the type and concentration of anions present in the environment and the ambient temperature [59].

Our research shows that bottom sediment can be used in agriculture because it has a positive effect on plant yield. However, a positive effect of bottom sediment on mustard yield we found on the treatment with a lower dose of bottom sediment. We suppose that the higher doses of bottom sediment decreased the yield caused by the unfavorable air-water conditions in the formed substratum. A similar effect of bottom sediment was observed by other authors [9,18,19]. They found that doses 0–10% of the sediment significantly increased yield of maize. Additionally, the same research showed that highest dose of sediment, between 14% and 16%, caused a decrease in the yield of the plants. The dredged sediment rich in nutrients (NPK), organic carbon, and microbial activity can be used as fertilizer substitutes for crop production. Bottom sediment, especially with neutral or alkaline reaction and high contents of silt and clay fractions, influences physicochemical properties of sandy and acid soils and improves their productivity [9,18,19]. Fonseca et al. [47] found that bottom sediment from water reservoirs in Portugal and Brazil was suitable for use as fertilizers and presented no threats to the environment. Darmody and Diaz [60] suggested using the sediment obtained in the process of dredging the Illinois River to enrich sandy soils with nutrients and use these soils for agricultural production. Canet et al. [61] found that increasing the dose of bottom sediment from a lake increased the yield of lettuce, but the tomato yield remained unchanged. The bioavailability of metals in soil is a dynamic process that depends on specific combinations of chemical, biological, and environmental parameters. Metals distribution in plants is very heterogenous and is controlled by genetic and environmental factors.

The dynamics of heavy metals in plant-soil interactions depends mainly on the levels of soil contamination and plant species [44]. The conducted research showed that each type of sediment tested increased the content of the Cd, Zn, and Pb in plants. No influence of bottom sediment on the copper content in plants was found (Figure 3). Karak and Bhattacharyya [62] found that the use of bottom sediment in wheat cultivation increases the content of Zn and Cu, improving its quality. The researchers did not observe an increase in heavy metal content in the examined plants by increasing the dose. Similar results were obtained by Chabchoubi et al. [63], who found that the content of Zn, Cd and Mn increases in the analyzed grasses, but their content did not exceed the acceptable standards, making the plants suitable as fodder. As shown by Tarnawski et al. [18] the bottom sediment supplements to light soil caused an increase in copper, nickel, chromium, and lead in maize shoot biomass in relation to the control treatment. Usually, the content of studied metals increased with dose of bottom sediment. Zinc and cadmium content was not markedly dependent on the applied amount of bottom sediment. Regardless of the bottom sediment dose, a decline in zinc and cadmium content, ranging from 23% to 30% in comparison with the control, was noted in the maize shoots.

The values of the TF factor prove that the heavy metals studied are highly bioavailable and transfer easily from soil to plant. Zhang et al. [64] pointed out that TFs can be considered as a useful index of metals potentially transfer abilities from soil to plant. In our study the highest values of the TF were obtained for Zn, and the lowest for Pb. The value of TF depends on the plant species, the levels of the metals in the soil and the chemical nature of metal. The metals transfer from the soil to the plants is influenced by a variety of soil parameters, such as: pH and Eh values, fine grain fraction (<0.02 mm), organic matter, oxides, and hydroxides content and multiple other factors, such as climatic condition, vegetation period etc. [42,44]. In the studies of other authors large variations in TF value were observed among different plants and metals. However, usually the highest values of TF are observed for Cd and Zn, and the lowest for Pb [42,44,65]. Cadmium and zinc are more easily taken up by plants because they are more mobile in the soil than lead. Metals can be arranged according to their affinities for the soil in the following sequence: Pb > Cu > Cd > Zn [43,65,66].

5. Conclusions

The conducted research proves the possibility of using bottom sediment for crop fertilization. The examined types of bottom sediment were characterized by a high content of silt fractions (6–28%) and a neutral/alkaline pH, which makes it suitable for use on sandy and acidic soils. Results indicate that adding bottom sediment resulted in significant increases in plant yields relative to controls. The higher mustard yields were achieved with the addition of bottom sediment in doses up to 10%. Highest yields in year one were obtained with a 5% addition of dam sediment, while second-year benefits were highest for a mix with 10% addition of pond sediment. The values of a postulated transfer factor (total elemental concentration in plant/corresponding elemental concentration in soil) indicate a high accumulation of zinc and low accumulation of lead in the white mustard. The values of the TF factor indicate a high mobility of zinc and cadmium along with a moderate, and very low, mobility of copper and lead, respectively. In terms of the TF factor, the examined metals can be arranged in the following order Zn > Cd > Cu > Pb.

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