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AN ASSESSMENT OF BOTTOM SEDIMENT AS A SOURCE OF PLANT NUTRIENTS AND AN AGENT FOR IMPROVING SOIL PROPERTIES

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Abstract

We studied the effects of bottom sediments on the physical and chemical fertility of a sandy soil, and on the biomass production and chemical composition of maize and field beans plants grown on the soil/sediment mixes. The studied sediments had high clay content and neutral pH value. The sediment was mixed with soil in the following doses: 5%, 10%, 20%, 30% and 50% on a dry weight basis. The results showed that mixing with sediments increased the soil pH value, the contents of organic C and N, and the availability of P, K and Mg. Mixing with sediments resulted in greater yield of maize and field beans, in particular after the application of the highest dose of bottom sediment (50%), while the lowest dose (5%) generated significantly higher plant yield only for field beans. Results showed also that both plants absorbed less N, K and P as compared to the control treatment, indicating the need of supplementary mineral fertilization in case of use of bottom sediments as growing media. The legal implications of the potential reuse of bottom sediments in agriculture are also discussed.

Key words: agriculture use, bottom sediment, improve soil properties, plants growth

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1. Introduction

Loss of water storage due to sediment accumulation processes within a reservoir is one of the key focuses of sustainable reservoir management (Walter et al., 2012). The dredging of sediments accumulated in the bottom of the reservoir, as well as lakes, rivers and coastal areas has been proposed as a suitable solution to alleviate the problem of siltation (Canet et al., 2003; Ebss et al., 2007; Macía et al., 2014; Mattei et al., 2017; Sheehan et al., 2010; Tarnawski et al., 2017). However, this operation generates enormous volumes of sediments that must be either disposed of or used for production purposes (Urbaniak et al., 2016; Wyrwicka et al., 2014). Nowadays, the management of dredged sediments is a global issue, especially considering that regulations governing this are still not available (Mattei et al., 2017; Todaro et al., 2018). Moreover, these materials, ranging from rocks to clays, can contain a variable amount of organic matter as well as different types and levels of contaminants. Consequently, the evaluation of sediment properties, before deciding if the dredged materials are acceptable for beneficial use, is important not only for the assessment of water reservoir sediments, but also for determining the potential applications of dredged sediment (Baran et al., 2015; Mamindy-Pajany et al., 2012; Perrodin et al., 2006; Siham et al., 2008; Tarnawski et al., 2017).

Several possibilities for the beneficial use of dredged sediments have been recognized, e.g.: erosion control, aquaculture, forestry, shoreline stabilization,

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manufacture aggregates, construction uses, and energy production (Mattei, et al. 2017; Siham et al., 2008; Zentar et al., 2013). For economical, technical and ecological reasons, most of the uncontaminated or slightly contaminated, dredged sediments should ultimately be used in agriculture (Baran et al., 2011; Bartoszek et al. 2015; Canet et al., 2003; Karanam et al., 2008; Terziyski et al., 2014).

The agricultural utilizations of sediments is of the most promising alternatives due to the beneficial properties of sediments that are rich in clay, silt, organic matter, nutrients (macro- and micronutrition), and microbial activity (Baran et al., 2012; Canet et. al., 2003; Catianis et al., 2018; Ebbs et al., 2006; Fonseca et al., 2003; Jasiewicz et al., 2010; Tarnawski et al., 2015, Wiśniowska-Kielian and Niemiec, 2007a, 2007b; Walter et al., 2012). Mattei et al. (2017) assessed the co-composting of sediments with urban green waste as a sustainable technique to provide sediments with suitable properties to be reused as technosol. Sheehan et al. (2010) found the production of manufactured topsoil from dredged sediments to be technically viable and that it compares well with market standards after treatment.

Considering the above, the aim of the study was to investigate the effects of the application of dredged sediment (Rzeszów Reservoir, South-eastern Poland) on 1) the physical and chemical properties of sandy soil, and 2) the yield of two selected crops: maize and field beans, in order to evaluate the reasonableness of agriculture sediment utilization as well as to develop an effective sediment management strategy in the future.

2. Material and methods

2.1. Study area and sampling

The bottom sediments came from the Rzeszów Reservoir situated on the Wisłok River in the Podkarpackie Voivodeship, South-eastern Poland (Fig. 1). The main task of the reservoir is to enable the functioning of the water intake, protection against flooding as well as recreation (Michalec and Tarnawski, 2008; Tarnawski and Baran, 2018). With a total primary capacity of 1.8 million m^3 and an area of 68.2 ha, the reservoir is characterized by an elongated shape of approx. 6.74 km and a variable width. Based on the latest bathymetric measurements (2014), the volume of the Rzeszów Reservoir amounts to 0.682 million m^3, constituting 38% of its initial capacity. This indicates an intense course of the reservoir silting processes. A further progressive process of the loss of reservoir capacity poses a significant threat to the operation of the water intake. Moreover, the reservoir is located in an area of urban development, which creates further hazards in the event of a flood or an increase of the groundwater level. Further shallowing of the reservoir will result in a threat to valuable habitats of plants and animals by slowing down the self-cleaning processes, which will result in a deterioration of the water quality, an increase of the water temperature as well as an increase of the nitrogen and phosphorus content. An intense reservoir eutrophication process will lead to a complete loss of its recreational function for the residents of the city. The above reasons determine the necessity to undertake desilting works as an opportunity to rescue the multitasking of the reservoir, taking its valuable natural character into account.

The samples of sediment were taken from three zones of the Rzeszów reservoir: inlet, middle and outlet, using an Ekman sampler (Fig. 1). The sediments were sampled from the 0-15 cm layer and mixed to form the final averaged sample.

2.2. Properties of bottom sediments

Before the experiment started, a chemical characterisation of the sediments was preformed (Table 1). Considering the texture of the sediments, the clay fraction dominated, constituting 54%, while silt and sand constituted 38% and 8% of the sediment composition, respectively. The sediments have a pH of 7.1. The content of organic carbon was low - 23.5 g kg^{-1}. Moreover, it had a moderate content of available P and K as well as a relatively high content of Ca and Mg. It should be noted that currently in Poland, there is no legal possibility to recover the bottom sediment "spoil" coming from the dredging of water reservoirs using the R10 method - "Land treatment resulting in a benefit to agriculture or improving the environment as well as the types of waste acceptable for such recovery" (Journal of Laws-item 130, 2015). Therefore, the Regulation of the Minister of the Environment of the 11th May 2015 on the recovery of waste outside installations and equipment (Journal of Laws, 2015; item 795) was used to assess the quality of the examined bottom sediments. The content of trace elements in the analyzed sediment did not exceed the permissible level established for sediments (Journal of Laws, 2015; item 795).

This content was additionally assessed based on Bojakowska's geochemical quality classes of bottom sediments (Tarnawski and Baran, 2018). There are four classes: I - non-contaminated sediments, II - moderately contaminated sediments, III - highly contaminated sediments, and IV - very highly contaminated sediments (Bojakowska, 2001). According to this criterion, the sediment was classified as class II (moderately contaminated sediments) due to an elevated concentration of Cd.

In the case of soil used in the experiment, sand was the dominant fraction. The soil had an acidic reaction and low content of organic carbon as well as available P, K and trace elements (Table 1).

2.3. Scheme of pot experiment

Five doses of sediments were assessed as part of a pot experiment conducted inside a temperature and moisture controlled vegetation hall, and compared with the control (without sediment application).

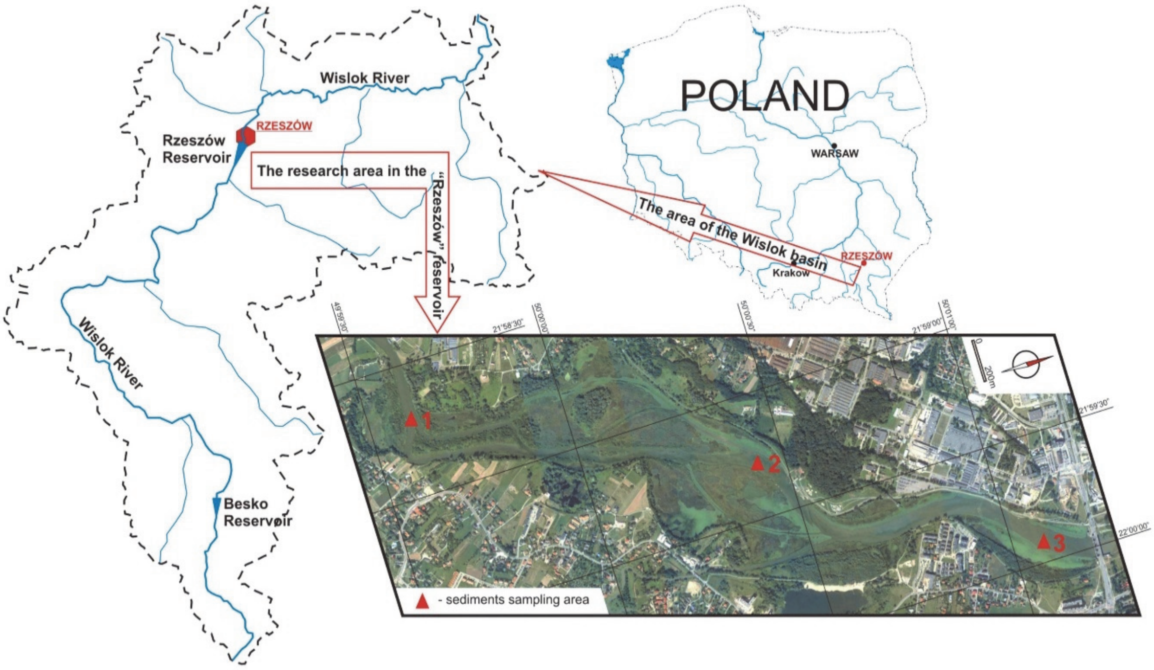

Fig. 1. Localization of the Rzeszow Reservoir and sediment sampling areas

Table 1. Selected properties of bottom sediment and soil

Material	***Texture %***			***pH***	***C***	***N***	***P_2O_5***	***K_2O***
	sand	***silt***	***clay***	***KCl***	***g kg^{-1}d.m***		***mg kg^{-1}d.m.***	
Bottom sediment	8	38	54	7.1	23.5	2.3	144	212
Soil	68	23	9	5.5	15.6	1.2	70.4	112
Material	***Zn***	***Cu***	***Ni***	***Pb***	***Cd***	***Mn***	***Ca***	***Mg***
	mg · kg^{-1}						g · kg^{-1}	
Bottom sediment	106.8	20.9	33.5	19.6	4.5	650	19.53	5.44
Soil	50.0	31.4	13.9	12.2	0.45	136.9	-*	-

**not analysed*

The bottom sediments in doses of 5%, 10%, 20%, 30% and 50% were added to the soil. All treatments were prepared in 4 replications, in pots with a capacity of 6 kg. Mineral N, P, K fertilization was applied according to the individual needs of plants. The test plants were maize (*Zea mays*), Bora c.v., and field beans (*Vicia faba*), Amulet, c.v. During the vegetation period, the plants were watered with de-mineralised water and a constant moisture of the growing media was maintained, initially on a level of up to 50% and then of up to 60% of the maximum water capacity. The test plants were harvested after 86 (maize) and 60 (field beans) days of vegetation. After harvesting, the plant material was dried at 65^{o}C in a dryer with forced air flow and the amount of dry mass yield was determined. Subsequently, the plant material was crushed in a laboratory mill and subjected to chemical analysis.

2.4. Chemical analysis

The contents of macronutrients (K, P, Na, Mg, Ca) and trace elements (Mn, Zn, Cd, Pb, Ni, Cu) were determined in the plant materials using the ICP-OAS method after dry digestion and dissolving the ash in HNO_3 (1:3) (Baran et al., 2016). The N content was assessed using the Kjeldahl distilling method. After the pot experiment, the soil samples were analyzed: pH, content of C org., total N, P, K and trace elements (Mn, Zn, Cu, Ni, Pb, Cd). In the growing media content of organic carbon, total nitrogen and pH_{KCl} was assessed. Organic carbon and total N content was analysed using an Elementar Vario MAX cube CNS analysed and pH using potentiometric method and 1:2.5 sediment: liquid ratio.

The available forms of K and P were analysed by the Egnera - Riehma method. Soluble forms of Zn, Cu, Ni, Pb, Cr, Cd were extracted from the substratum, with a 1 mol dm^{-3} HCl solution (Rinkis method) (Novozamski et al., 1993). The extraction of trace elements from the growing media was conducted using a static method, by means of a single shaking of the soil samples with the solution at a soil to solution ratio of 1:10 and during an extraction time of one hour. This is a routine and commonly used method in agricultural chemistry stations in Poland for assessing the content of the available forms of microelements in the soil.

The contents of elements in the solutions were assessed using ICP-OES methods (Inductively Coupled Plasma Atomic Emission Spectroscopy) on Optima 7300 DV (Perkin-Elmer). The accuracy of the analyses was determined using reference material CRM 16-05, Soil Standard Loamy batch no. 133505 and BCR 129. The percentage of recovery was between 81 (Cu) to 114% (Pb), from 91 (N) to 105% (organic C) for bottom sediments and soil samples. For the plant material the percentage of recovery ranged from 103 (Ca) to 112% (Mg).

2.5. Statistical analysis

Four replications of plant and soil samples were assessed. If the relative standard deviation (RSD) did not exceed 5%, the result was correct. The results were verified statistically using one factor ANOVA and Tukey test at a significance level $\alpha < 0.05$. A Microsoft Excel 2007 spreadsheet and the Statistica 12 package were used for the analysis and presentation of the results.

3. Results and discussion

3.1. Properties of soil after experiment

Selected properties of the soil were presented in Table 2. The study showed that the sediment supplement to the soil caused a significant increase in the soil pH value ranging from 36% (5% sediment supplement) to 55% (30% and 50% doses of the sediment) in compare to the treatment without of sediment. These results confirmed the de-acidifying effects of the bottom sediments of the Rzeszów Reservoir (Kaczmarski and Jasiewicz, 2013). Our previous study also proved that the application of bottom sediments with pH above 6.7 may have a de-acidifying effect on the soil (Baran et al., 2009, 2010, 2011; Tarnawski et al., 2015). This effect is particularly interesting since the application of the Rzeszow sediments can limit the toxic effect of heavy metal.

We found that using all doses of the sediment caused a significant increase in the content of organic carbon in compared to the control (soil without of sediments). The highest content of organic C was found in the case of treatment with an addition of 5% of bottom sediment. The increase of organic carbon together with the clay content gave rise to an increase in the cation exchange capacity of soil (Canet et al., 2003). Therefore, this application could help prevent nutrient deficiencies, which are very common in light soil with the dominance of the sand fraction. Sediment supplements to soil did not significantly affect the total N content. The highest content of N was found in the case of treatment with 30% and the lowest with 5% of sediment supplement (Table 2). An important parameter in the soil environment is the C:N ratio, as it determines the rate of organic matter mineralization: the lower the ratio, the higher the degree of mineralisation. In the studied treatments, the C:N ratio fluctuated from 9 to 18 (Table 2). Sediment amended to the soil caused a significant increase of the available forms of P, K and Mg in relation to the control treatment (Table 2). The highest content of these macronutrients was observed in the treatment with a 50% and 30% addition of the sediment. The content of available forms of P and K in soil with bottom sediment was high and very high.

Content of trace elements in growing media with diffrent doses of bottom sediments is shown in Table 3. The used doses of bottom sediments significantly increased the content of available forms of trace elements, being 1.2 to 2.1-fold for Mn, from 0.8 to 1.2-fold for Zn, from 1.0 to 0 2.9-fold for Cu, and from 1.5 to 3.8-fold for Ni, which is higher in comparison to the control. In the treatment with the highest dose of sediment (50%) was observed the highest content of the above elements. Doses of bottom sediment significantly reduced the content of toxic elements: the content of soluble Cd decreased from 2.1 to 2.8-fold. Also, the content of Pb was 1.1. to 1.2-fold lower in relation to the control treatment.

Bottom sediments from the Rzeszów Reservoir are rich in clay and calcium carbonate (Baran et al., 2015; Tarnawski and Baran, 2018). These properties are decisive when it comes to the buffering capacity of the sediment in terms of pH changes. It is important that, with the alkaline reaction resulting from the presence of carbonates, the mobility of metals in the environment is limited. Moreover, the total content of trace elements is an important indicator of soil contamination, but it cannot provide information on the mobility of elements (Kim et al., 2015; Wieczorek et al., 2018). In the in-balanced fertilization, knowledge about the content of readily soluble metal forms is particularly useful due to their possible mobilization from the solid phase and moving into plants.

Table 2. Effect of the sediment application on change of pH and content of organic carbon, N, and available forms of P, K, Mg

Treatment	***pH***	***Organic C***	***Total N***	***C:N***	***P_2O_5***	***K_2O***	***Mg***
		g kg^{-1} d.m.			***mg kg^{-1} d.m.***		
Kontrol	4.72 a*	7.63 a	0.83 a	9 a	134 a	178 a	73.03 a
5% sediment	6.42 b	12.79 b	0.72 a	18 b	203 b	185 a	93.37 bc
10% sediment	7.02 c	12.21 b	0.92 a	13 ab	253 bc	180 a	90.23 b
20% sediment	7.24 c	12.60 b	0.94 a	13 ab	257 bc	219 ab	99.03 bc
30% sediment	7.31 d	11.66 b	1.00 a	12 ab	259 bc	260 b	104.0 c
50% sediment	7.31 d	10.56 b	0.93 a	12 ab	278 c	246 b	125.8 d

**homogenous groups according to Tukey test, $\alpha < 0.05$*

3.2. Yield and chemical composition of plants

The application of sediments increased the yield of maize and field beans, and no negative effects caused by salts and pollutants were observed (Table 4). In the case of both tested plants, the highest yield was observed in the treatment with a 50% addition of the sediment, being about 20% (maize) and 30% (field beans) higher in comparison to the control treatment (Table 4). The highest shoot, root and whole plant yield was observed for maize when a 50% admixture of bottom sediment was used. On the contrary, significant effects on the yield of field beans were found in the treatment with 5% of bottom sediment (shoots and whole plants).

Table 5 presents the effects of sediment application on the macronutrient contents in plants. In all cases, significant effects were observed, depending on doses of sediment and plants. Sediment supplements to soil caused a significant increase of Mg, Ca and N contents (doses of 5% - 20% sediment) in maize shoots in relation to the control, while the K, P and Na content showed a significantly relevant decrease (Table 5). The lower content of K and P, and also N (doses of 30 and 50% of sediments) can be related to the higher production of maize biomass. The effect of the sediments on the macronutrient content in field beans was slightly different (Table 5). Sediment supplements to soil caused an increase in Ca, Mg, N and Na in plant shoots in relation to the control treatment. However, similarly as for the maize, the application of sediment in all doses led to a significant decrease of K and P contents in field bean shoots. Considering the above, the results showed that bottom sediments from the Rzeszów Reservoir can be an important source of calcium and magnesium for plants

Despite the changes in macronutrients, the contents of trace elements in the shoots of both plants have been evaluated (Table 6). Sediment supplements to soil decreases the content of Mn, Zn, Ni, Pb and Cd in the studied plant shoots. On the other hand, it increases the content of Cu in relation to control plants. The highest content of trace elements in maize shoots was registered after 50% (Mn, Zn, Pb, Cd), 30% (Cu) and 5% supplementation of bottom sediment (Ni). The effects of the application of sediments on the content of trace elements in field bean shoots were remarkably different. The highest content of Mn, Zn, Pb, Cd was registered for plants grown in soil amended with a 5% dose of bottom sediment, and Ni and Cu in variants with a dose of 50% of bottom sediment.

Table 3. Effect of the sediment application on the contents of trace elements in the soil

Treatment	***Mn***	***Zn***	***Cu***	***Ni***	***Pb***	***Cd***
	mg kg^{-1} d.m					
Kontrol	136.9 a	16.92 bc	0.75 a	0.60 a	14.34 b	1.33 b
5% sediment	173.5 a	13.98 a	1.32 b	0.89 b	12.87 ab	0.62 a
10% sediment	217.6 b	14.89 ab	1.75 c	1.18 c	13.10 ab	0.55 a
20% sediment	267.4 c	17.61 cd	2.79 d	1.76 d	13.05 ab	0.51 a
30% sediment	289.6 d	19.57 d	3.78 e	2.30 e	12.35 a	0.50 a
50% sediment	366.4 e	24.48 e	6.58 f	3.62 f	12.21 a	0.48 a

**homogenous groups according to Tukey test, α < 0.05*

Table 4. Effect of the sediment application on the yield of maize and filed beans

Treatment	***Maize (g pot^{-1} d.m)***			***Filed beans (g pot^{-1} d.m)***		
	Shoots	***Roots***	***Whole plants***	***Shoots***	***Roots***	***Whole plants***
Kontrol	118.50 a*	31.17 a	149.67 a	44.04 a	13.54 ab	57.58 a
5% sediment	133.50 ab	23.67 a	157.17 a	67.88 b	13.02 ab	80.91 b
10% sediment	128.00 ab	21.00 a	149.00 a	75.50 b	10.17 a	85.67 bc
20% sediment	123.83 ab	23.83 a	147.67 a	65.51 b	9.97 a	75.49 b
30% sediment	125.50 ab	27.00 a	152.50 a	75.81 b	9.57 a	85.38 bc
50% sediment	144.83 b	39.83 a	184.67 b	76.38 b	15.20 b	91.58 c

**homogenous groups according to Tukey test, α < 0.05*

Table 5. Effect of the sediment application on the content of macronutrients (K, P, Ca, Mg, N, Na) in the plant shoots

Treatment	***Maize (g kg^{-1} d.m)***					
	K	***P***	***Ca***	***Mg***	***N***	***Na***
Kontrol	17.83 c*	2.53 c	2.50 a	1.87 a	10.70 b	18.92 b
5% sediment	14.60 a	1.31 ab	3.12 ab	2.24 b	11.46 bc	16.41 ab
10% sediment	16.88 abc	1.41 b	3.65 bc	2.11 ab	11.91 c	13.76 ab
20% sediment	17.36 bc	1.32 ab	4.23 c	2.52 c	14.25 d	12.46 a
30% sediment	16.79 abc	1.27 ab	3.84 bc	2.61 c	4.41 a	16.27 ab
50% sediment	15.02 ab	1.07 a	3.78 bc	3.01 d	4.73 a	17.10 ab
Treatment	***Filed beans (g kg^{-1} d.m)***					
	K	***P***	***Ca***	***Mg***	***N***	***Na***

Kontrol	9.16 b	3.79 c	12.01a	1.91 a	21.66 a	0.10 a
5% sediment	8.11 ab	3.41 c	13.17 ab	2.10 ab	25.97 b	0.13 b
10% sediment	8.96 ab	2.71 ab	12.58 ab	2.36 ab	25.43 b	0.15 c
20% sediment	8.62 ab	2.78 ab	13.54 ab	2.27 ab	24.28 b	0.24 d
30% sediment	8.20 ab	2.87 b	13.78 b	2.45 b	25.31 b	0.33 e
50% sediment	7.68 a	2.56 a	13.70 b	2.40 b	25.29 b	0.46 f

Table 6. Effect of the sediment application on the content of trace elements (Mn, Zn, Cu, Ni, Pb, Cd) in the plant shoots

Treatment	***Maize (mg·kg⁻¹ d.m)***					
	Mn	***Zn***	***Cu***	***Ni***	***Pb***	***Cd***
Kontrol	86.29 c*	48.63 c	1.67 a	1.15 b	0.52 b	0.31 c
5% sediment	43.92 b	32.40 ab	1.87 ab	1.12 b	0.42 ab	0.07 a
10% sediment	26.39 a	25.40 a	1.91 ab	0.62 a	0.34 a	0.09 ab
20% sediment	47.55 b	29.90 ab	2.34 b	0.76 a	0.43 ab	0.09 ab
30% sediment	49.97 b	29.86 ab	3.01 c	0.65 a	0.35 a	0.08 ab
50% sediment	85.75 c	36.75 b	2.91 c	0.97 a	0.49 b	0.13 b
Treatment	***Filed beans (mg kg⁻¹ d.m)***					
	Mn	***Zn***	***Cu***	***Ni***	***Pb***	***Cd***
Kontrol	446.57 c	159.43 c	4.95 a	2.81 b	2.58 b	2.56 c
5% sediment	118.27 b	70.92 b	4.55 a	1.27 a	2.05 ab	0.43 b
10% sediment	76.70 a	55.68 b	5.57 ab	1.11 a	1.88 ab	0.33 ab
20% sediment	84.41 a	24.52 a	5.60 ab	1.29 a	1.61 a	0.20 ab
30% sediment	91.09 a	29.88 a	6.75 b	1.59 a	1.53 a	0.18 ab
50% sediment	86.49 a	27.14 a	6.92 b	2.52 b	1.35 a	0.11 a

The degree of accumulation of trace elements in plants was assessed using the bioaccumulation coefficient (BC), calculated as a ratio of the content of elements in shoots to the content of elements in the growing media (Baran, 2012; Augustynowicz et al., 2014). It was found that the bioaccumulation of trace elements by field beans was around 3.2-fold (Mn), 1.9-fold (Zn, Ni), 2.6-fold (Cu), 4.0-fold (Pb) and 3.8-fold (Cd) higher than by maize (Fig. 2). Moreover, the calculated BC values showed that plants accumulated Zn, Cu and Ni (the highest values of BC) more easily than Mn, Cd and Pb. In the treatment with sediments, a high accumulation rate (BC > 1) was observed for Zn (all doses of sediment, both plants), Cu (field beans - all doses of sediment, maize - 5 and 10% of doses of sediment), Ni (both plants, 5% of doses of sediment), whereas the Mn, Cd (both plants), Ni (both plants, 10 – 50% of doses of sediment), Cu (maize, 20 – 50% of doses of sediment) and Pb (field beans) produced moderate accumulation (BC 0.1-1). Only Pb in maize was found to be accumulated to a low extent (BC 0.01-1). However, regardless of the plant species, the application of sediments significantly diminished the BC value of about 59 - 93% for Mn, 19-88% for Zn; 36 - 84% for Cu, 31- 83% for Ni; 22-40% for Pb; 7-89% for Cd in comparison to the control treatment. The above effect of sediment application was beneficial from the point of view of decreasing the accumulation of toxic metals, such as Pb and Cd, in the studied plants. However, it also caused a low content of micronutrients (Mn, Zn, Cu, Ni) in plants.

The important agents affecting the mobility and bioavailability of trace elements from soil to plants include reaction, organic C content and grain size distribution (Kim et al., 2015; Wieczorek et al., 2018). Bottom sediments from the Rzeszów Reservoir were classified as a group of clay deposits with a neutral reaction. These properties might have influenced the decreased mobility of the trace elements from the treatments with a supplement of bottom sediment to plants. In a neutral or slightly alkaline soil reaction, trace elements occur primarily and are specifically adsorbed at hydroxyl surfaces of oxides or clay minerals (Kim et al., 2015). This specific adsorption is associated with the composition of inner sphere complexes of metal hydroxides via covalent bonding. Therefore, the trace elements exhibiting a high level of specific adsorption are generally less mobile and available. On the other hand, at low pH, trace elements exist mainly non-specifically and are adsorbed at the binding sites of cation exchange of clay minerals and oxides via electrostatic bonds, which are related to the exchangeable, easy mobile fraction of trace elements (Kim et al., 2015; Wieczorek et al., 2018). In the studies, there was an observed higher content of trace elements in plants and higher values of BC in the control treatment compared to treatments with doses of bottom sediments. The soil used in experiment was characterized by an acid reaction (Table 1, 6 and Fig. 2). Moreover, in alkaline bottom sediments, calcium carbonate decides on the buffering capacity of the sediment in terms of pH changes (Al-Mur et al., 2017). It is worth noting that the sediments contained quite a lot of calcium carbonate, which constitutes a backup form of Ca. This is especially important from the point of view of high Ca leachability and its significant removal with plant yield. Calcium carbonate impacts the soil in structure-forming terms and favors the formation of organic matter as well as the accumulation of humus (Tarnawski et al., 2017). The bioavailability of trace elements is related not only to soil/sediment factors, but also is depended on species, the development stage, part of plant and metal types (Alexander et al., 2006; Kim et al., 2015). Many authors revealed that monocots are less sensitive to soil pollution with trace elements compared to dicotyledons (An, 2004; Baran, 2013). Generally, dicotyledons are more sensitive to trace element stress, which results from their translocation from roots to shoots at the earliest development stages (Baran, 2012). In this study, the above information that maize showed less bioaccumulation of trace metals compared to field bean was confirmed.

Since both tested plants can be used as animal feed, the study assessed the effect of bottom sediment application to the soil on both the content of macronutrients and the content of trace elements in the tested plants. The optimal macronutrient content amounts to: 30-50g N; 3.0 – 6.0g P; 30-45g K; 2.0-6.0g Mg and 3.0-10g Ca ·kg^{-1} d.m. (Baran et al., 2016). The permissible contents of trace elements in feeds are: Zn < 100 mg; Cu < 30 mg; Ni < 50 mg, Cd < 0.5 mg and Pb < 10 mg ·kg^{-1}d.m. (Kabata-Pendias et al., 1993). The excessive or toxic contents of trace elements in plants amount to: >5-10 mg Cd; >150-400 mg Zn; >20-30 mg Ni; >20-100 mg Cu and >10-20 Pb kg^{-1}d.m. (Kim et al., 2015). Plant shoot biomass in treatments with bottom sediments revealed a deficient content of K, P (except: field beans, 5% of sediment doses) and N, but an optimal content of Ca and Mg. The assessment of the content of trace elements in maize and field bean shoots demonstrated the suitability of those plants for animal feed production.

However, in the case of trace elements, their content was deficient in the studied plants. The excessive zinc content was only found for field bean shoots in the control treatment (without sediments).

The application of dredged material from the reservoir on terrestrial soils generally should not reduce soil quality. All soil functions, including water storage, nutrient retention potential, available nutrient concentration, biodiversity and microbial activity, have to be conserved (Walter et al., 2012). In the present study, sediments from the Rzeszów Reservoir revealed a neutral reaction high content of silt and clay fractions, and low concentrations of trace elements. Consequently, it can be used as an addition to light acid soils to improve their productivity and reduce the toxic effect of heavy metals on the soil and plants.

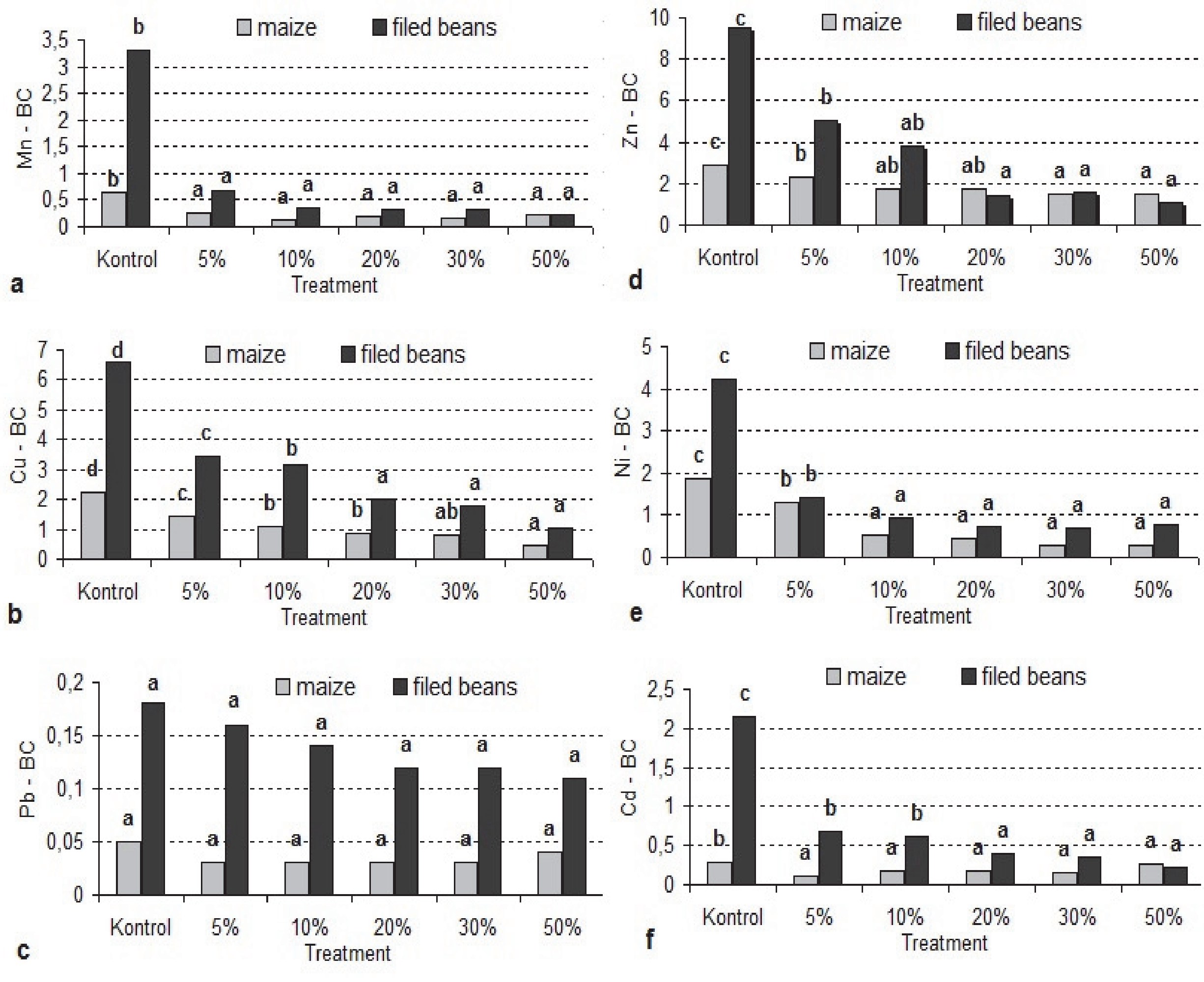

Fig. 2. Bioacumulation coefficient of trace elements in plants: Mn (a), Cu (b), Pb (c), Zn (d), Ni (e), Cd (f)

The results demonstrated a significant effect of the applied sediments on the improvement of the soil pH and the content of organic carbon, total N, available forms of P, K, Mg. It was also found that bottom sediments added to the soil significantly increased the content of soluble forms of Mn, Zn, Cu and Ni, and decreased the concentration of toxic metals: Cd and Pb. Similar results were obtained in our earlier studies focused on the agricultural application of sediments from different reservoirs (Baran et al., 2009, 2016; Tarnawski et al., 2015). However, our previous studies found that the ecological risk assessment of the metals and polyaromatic hydrocarbons (PAHs) revealed a high potential toxicity in sediments from the inlet zone (PECq = 0.69) and the outlet zone (near the dam) (PECq = 0.56) and a low potential toxicity in sediments from the middle part of the reservoir (PECq = 0.38) (Tarnawski et al., 2018). Moreover, in the studies of Bartoszek et al. (2015) found that sediment form Rzeszów Reservoir is not suitable for agricultural use due to contamination and poor of fertility. These sediments can be used for non-agricultural land reclamation. Considering the above ecological risk, it is important to provide a comprehensive analysis of the quality and quantity of bottom sediments before their utilization in agriculture.

Several national and global studies have been undertaken to elucidate the effect of sediment application on soil properties and plants biomass, e.g. Kaczmarski and Jasiewicz (2013) found that the application of bottom sediment to acid soil reduced their level of acidification. They also found that the content of soluble forms of Cu and Zn in soil increased as a consequence of increased sediment doses introduced to the substratum. Canet et al. (2003) observed the most relevant changes of soil properties after the application of sediments from the Albufera Lake (eastern Spain). Sediments improved the soil water retention and cation exchange capacity; however, they also increased salinity and heavy metal concentration in the substratum (Canet et al., 2003). Baran et al. (2012, 2013, 2016) and Jasiewicz et al. (2011) demonstrated a positive effect of the bottom sediments from the Besko, Zesławice and Narożniki Reservoirs (Southern and Eastern Poland) on maize biomass production and its chemical composition. The authors showed that the largest yield of maize was obtained in variants with the smallest applied dose of bottom sediment (5%).

Higher doses led to a depression in yielding, caused by unfavorable air conditions in the substratum. The different experiments found a positive effect of soil enriched with bottom sediments on the production of plants, e.g. pepper (Fonseca et al., 1998), lettuce, tomato (Canet et al., 2003), maize, mustard (Wiśniowska and Niemiec, 2007a, 2007b). In the present study, the highest yield of maize and field beans was measured when the highest doses of bottom sediment (50% of doses) were applied. Moreover, a significant effect of bottom sediment on the yield of field beans was observed at the lowest dose of sediment. During treatments with an admixture of bottom sediments, both plants had a deficient content of N, K and P, but optimal Mg and Ca concentrations. Low macronutrient contents indicate a necessity for the application of supplementary mineral fertilization in the agricultural use of bottom sediments. The content of micronutrients (Mn, Cu, Zn, Ni) was also deficient in the tested plants.

4. Conclusions

The chemical properties of bottom sediments from the Rzeszów Reservoir showed a high content of clay fractions and alkaline reaction. These properties predispose sediment to be used as a supplement that improves soil quality and productivity.

The content of trace elements in the sediments was below toxic thresholds; however, the content of nutrients (N, P, K) was also low. Consequently, the application of sediments from the Rzeszów Reservoir for agricultural would not an environmental risk. On the other hand bottom sediments cannot replace fertilizers.

The sediments, as a soil amendment, have an economical and environmental value. However, with respect to the variable chemical composition of bottom sediments, each batch intended for environmental use must be subjected to a chemical analysis and a biological assessment. Moreover, European and Local Agricultural and Environmental legislation should be modified to allow the re-use of non-contaminated sediments as soil amendments and growing media in agriculture.

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