Polish Journal of Agronomy
2019, 36, 8–16

doi: 10.26114/pja.iung.366.2019.36.02

The impact of a bottom sediment on the reaction and the content of exchangeable aluminium in a soil

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Abstract. The aim of the study was to determine the effect of bottom sediment on the pH and content of available forms of P, K, Mg and aluminium exchangeable in the soil and on the yield of oats.

The research was carried out in the Podlasie voivodship on very light soil. The material for the tests were samples of bottom sediment. In the experiment a bottom sediment from the breeding pond and soil was used. In the sediment bottom sediment sample, the following parameters were determined: pH, heavy metal content (lead, cadmium, zinc, copper), as well as the content of aluminum, phosphorus, potassium and magnesium. The reaction of the bottom sediment was also determined. In soil samples, the content of exchangeable aluminium, available forms of phosphorus, potassium, magnesium was determined and the soil reaction was determined.

The obtained results confirmed the influence of bottom sediment on reducing the content of exchangeable aluminium in the soil. The analyzes show that the soil after application of bottom sediment contained significantly less exchangeable aluminium. The sludge also influenced the increase of soil pH and the increase of magnesium content in the soil. There was no influence of the use of bottom sediment on the content of available phosphorus and potassium in the soil and on oat yield.

Keywords: bottom sediment, exchangeable aluminium, pH, macronutrients, trace elements, oat

INTRODUCTION

Water reservoirs are subject to systematically silting up. Over time, they require desilting and renovation. There are many ways to extract sediments, but there remains the problem of managing them (Madeyski, Tarnawski, 2006).

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Over the last 30 years, the content of active aluminium in soils all over the world has increased. This is caused by the process of decalcification (the leaching out of calcium compounds), which causes the acidification of soils. The decrease in the content of calcium ions in a soil is pertinent to not only arable soils, but also forests around the world (Bojorquez-Quintal et al., 2017). The increasing content of acid-forming oxides (SO_x and NO_x) in the air contributes to the acidification of the environment. In the northern hemisphere, the oxidation of sulphur to H_2SO_4 is considered to be the main cause of soil acidification. Poland stands out among other European countries for its large area of acidified soils (Gworek, 2006).

Approximately 50% of the soils used for cultivation should be limed (the Polish Central Statistical Office – GUS, 2017). Along with a decrease in a soil's reaction, there is an increase in the content of free aluminium ions in the soil. Free aluminium ions are toxic to plants. Aluminium causes damage to the root system in plants, blocks the dislocation of phosphorus, DNA replication and enzymatic processes (Bojorquez-Quintal et al., 2017).

A reduction in mobile forms of aluminium may also be achieved by means other than liming. For instance, while using gypsum does not change the reaction of a soil, it does have an impact on reducing the content of exchangeable aluminium in the soil, similarly to calcium carbonate (Łabętowicz et al., 2004).

Numerous publications on the toxicity of aluminium may be found in the relevant literature (e.g. Brzeziński, Barszczak, 2009). However, they do not address the issue of the influence exerted by a bottom sediment on the content of exchangeable aluminium in a soil.

This study assumes that there exists a way of limiting the negative effects that the impact of mobile aluminium has on plants by applying a bottom sediment. The specific aim of the study was to determine the impact of a bottom sediment on the yielding of oats, soil reaction, as well as the content of macroelements and exchangeable aluminium in the soil.

MATERIAL AND METHODS

The research was carried out at an agricultural holding in the village of Juszkowy Gród, Michałowo municipality, Bialystok poviat, Podlaskie Province. The experiment was established as split blocks in three replications on a leached out brown soil of the very weak wheat complex. The area dedicated to the research totalled 0.5 ha. The experiment covered the following combinations:

– plots K1 to K3: control treatment with no bottom sediment application,
– plots O1 to O3: bottom sediments applied in a dose of 50 Mg ha^{-1} in November 2015.

Neither mineral nor natural fertilizers were applied in the experiment. Chemical protection against weeds, diseases or pests was not used, either.

On 25.03.2016, the plots were planted to oats intended for grain.

Chemical analysis of the soil material

Soil samples for testing were collected from the two treatments, both before applying the bottom sediment, as well as after the oats harvest, from the depth of 0–20 cm. Approx. 15 partial samples were collected from each plot; these were subsequently mixed into one bulked sample. The collected soil was dried and sieved through a sieve with a mesh diameter of 2 mm.

The chemical analyses of soil samples included:

– determining the content of exchangeable aluminium using Sokołow's method after extraction in KCl with a concentration of 1 mol dm^{-3} – by applying the method of atomic absorption spectrometry (AAS) using a ThermoElementar apparatus (Ostrowska et al., 1991),
– determining the reaction in a KCl solution with a concentration of 1 mol dm^{-3} – by applying the potentiometric method using a Schott apparatus (ISO 10390: 2005),
– determining the content of available phosphorus and potassium by applying the Egner-Riehm method using a ThermoElementar apparatus (PN-R-04023: 1996, PN-R-04022:1996),
– determining the content of available magnesium by applying the Schachtschabel method – after extracting 0.0125 mol dm^{-3} with calcium chloride – by applying the method of atomic absorption spectrometry using a ThermoElementar apparatus (PN-R-04020:1994).

Chemical analysis of the bottom sediment

The research material consisted of samples of dried, grated and sieved bottom sediment. The bottom sediment was extracted from a fish pond with an area of 0.04 ha, located in the Podlaskie Province, on the territory of the Michałowo municipality, in the village of Juszkowy Gród. This pond is a permanent water reservoir. The bottom sediment was extracted from a naturally shallowed water reservoir.

The chemical analyses of samples included: determining the content of exchangeable aluminium, the reaction in a KCl solution, the content of available phosphorus, potassium and magnesium in accordance with the methodology used when analysing soil samples. In addition, the content of lead, cadmium, zinc and copper was determined after extracting in HCl at a concentration of 1 mol dm^{-3} – by applying the method of atomic absorption spectroscopy (AAS) using a ThermoElementar apparatus (Ostrowska et al., 1991).

Grain harvest assessment

The oats was harvested at the stage of collective maturity of the grain. In each of the 6 plots, samples from 3 sites, each with an area of 1 m^2 were collected at random and were then combined into a collective sample. The plants were scythed and subsequently bound into sheaves. The scythed plants were threshed by hand. Next, the yield from each of the 6 plots was determined (3 control stands and 3 stands fertilized with the bottom sediment).

Statistical analysis of the data

In the experiment, a design composed of randomized blocks with two stands in three replications was adopted. The collected experimental data were subjected to statistical analyses in the STATGRAPHICS Plus software and in an Excel spreadsheet. A two-factor analysis of variance at the statistical significance of $\alpha = 0.05$ and a correlation analysis were performed. The significance of differences between the means was evaluated using Tukey's test.

RESULTS AND DISCUSSION

Chemical analysis of the bottom sediment

According to the LAWA (1998) classification, bottom sediment is not contaminated with heavy metals and may therefore be used for agricultural purposes (Table 1). Studies by other authors also indicate that bottom sediments only contain small amounts of heavy metals and may be used for fertilization purposes (Gałka, Wiatkowski, 2010; Sammel, 2015; Niedźwiecki et al., 2007).

According to studies by many authors, bottom sediments demonstrate a significant share of the silt and clay fractions in their granulometric compositions and are characterized by a high alkaline reaction due to the high content of magnesium and calcium carbonate (Saeedi et al., 2011; Niemiec, 2006). The bottom sediment analysed in this study was characterized by a neutral reaction and (according to agricultural criteria) a low content of phosphorus and potassium, but a very high content of magnesium (Table

Table 1. The reaction and content of macronutrients and trace elements extracted in 1 mol dm^{-3} HCl in the analyzed bottom sediment.

pH in 1 mol dm^{-3} KCl (Reaction)	Exchangeable aluminium	Available phosphorus	Available potassium	Available magnesium	Lead	Cadmium	Zinc	Copper
	mg kg^{-1} DM of bottom sediment							
6.70 (Neutral)	0.48	25.60	51.46	166.00	0.64	0.017	2.38	0.33

1). According to Trojanowski and Antonowicz (2005), the content of elements available to plants in bottom sediments varies greatly depending on the place of collecting samples from the reservoir. Gałka and Wiatkowski (2010) also indicate that the sediments may vary for their content of macroelements that are available to plants – ranging from a very high to low (according to criteria for arable land). The content of mobile aluminium amounted to 0.48 mg kg^{-1} DM of the sediment (Table 1). Because no limit values have been set down for the content of mobile aluminium in bottom sediments, its content in the tested sediment could not estimated. As reported by Jaguś et al. (2012), aluminium oxide is one of the basic components of bottom sediments.

The assessment of the suitability of using bottom sediments for agricultural purposes, in addition to their content of heavy metals, also includes knowing their pH and the content of available forms of phosphorus, potassium and magnesium (Madeyski, 2006). When using a sediment for fertilization purposes, its neutral reaction is desirable because, according to the data of the Polish Central Statistical Office (GUS, 2017), in Poland, the share of soils with varying degrees of acidity (ranging from slightly acidic to very acidic) amounts to over 70%. When using a bottom sediment for fertilization, supplementary mineral fertilization should also be applied, due to sediments being poor in nutritional elements (N, P, K) (Baran et al., 2009; Wójcikowska-Kapusta et al., 2018).

The influence of the bottom sediment on the yields of oats

The content of water in a soil has a big influence on the yield of oats. The experiment was established on a very light soil with a small water capacity. This had an adverse effect on the yield of oats, which amounted to a maximum of 1.29 Mg ha^{-1} for the control treatment. The yield was also negatively influenced by the lack of chemical protection against pests and diseases. In the case of the third replication, in the combination where the bottom sediment was applied, only 0.84 Mg ha^{-1} of grains was obtained. On average, the yield in all the replications and treatments amounted to 1.02 Mg ha^{-1} of oat grains, and it was 61.51% lower than the average oat yield obtained in Poland in 2015 – 2.65 Mg ha^{-1} (GUS, 2015).

Table 2. Grain yield of oat [Mg·ha^{-1}] depending on fertilization.

K1	K2	K3	Mean	O1	O2	O3	Mean
1.29	0.94	1.06	1.09 a	1.13	0.85	0.84	0.94 a

K – control treatment; O – treatment fertilized with bottom sediment
Means from treatments signed with the same letter do not different significantly..

The statistical analysis did not demonstrate any influence of using the bottom sediment on the yield oats (Table 2). Niemiec (2006) also did not observe a beneficial effect of adding a bottom sediment on the amount of maize biomass produced. As indicated by Baran et al. (2013), bottom sediment has a positive effect on the yield, however, doses of above 5% cause a decrease in maize yields. The decrease in yields may result from the rise in the soil's pH under the influence of the calcium contained in the sediment (Baran et al., 1993; Niemiec, 2006). Many authors have noted the negative effects of increased soil reaction of the plant yields. Meanwhile, Arasimowicz et al. (2011) have demonstrated the beneficial effect of using a bottom sediment on the yields of mustard. The plants' yield increased significantly as the proportion of bottom sediment in the soil rose from 0 to 20%.

The influence of bottom sediment on the content of macroelements in the soil

Prior to establishing the experiment (November 2015), the soil was characterized by very high available phosphorus and moderately high available forms of potassium and magnesium (Table 3).

After harvesting the plants (August 2016), a significant decrease in the average content of available forms of phosphorus and potassium in the soil was found, both in the case of control plots, as well as those plots, to which the bottom sediment was applied. In control plots, the average content of available phosphorus decreased by 19%, and that of potassium by 32%, while in the plots where the bottom sediment was applied, the decrease amounted to 17% for P and 34% for K, respectively (Table 3, Fig. 1 and 2). Meanwhile, according to Baran et al. (2009) the addition of a bottom sediment causes a significant increase in the content of phosphorus available in the soil in comparison to the untreated control plots. The authors have demonstrated that adding five percent of the bottom sediment to the soil resulted in the content of phosphorus rising by 8%, while adding 10% of the bottom sediment – a 44% rise in the content of phosporus was recorded. Similarly to the present study, Baran et al. (2009) found that the application

Table 3. Content of available forms of macronutrients in soil [mg kg^{-1}] depending on term date of soil sampling.

Treatment	November 2015			August 2016		
	P	K	Mg	P	K	Mg
K1	63.66	85.49	28.02	34.80	75.53	29.02
K2	65.84	91.30	34.03	63.22	52.27	29.02
K3	71.94	49.80	11.01	64.53	26.56	10.01
Mean	67.15 aB	75.53 aB	24.35 aA	54.18 aA	51.45 aA	22.68 aA
O1	61.91	87.98	35.02	48.83	70.55	45.03
O2	70.63	95.45	42.03	60.60	61.42	41.02
O3	77.61	60.59	14.01	64.53	29.05	20.01
Mean	70.05 aB	81.34 aB	30.35 bA	57.99 aA	53.67 aA	35.35 bB

K – control treatment; O – treatment fertilized with bottom sediment

Small letters (a, b) denote significant differences between the means of treatments, and large letters (A, B) denote significant differences between the means of individual dates.

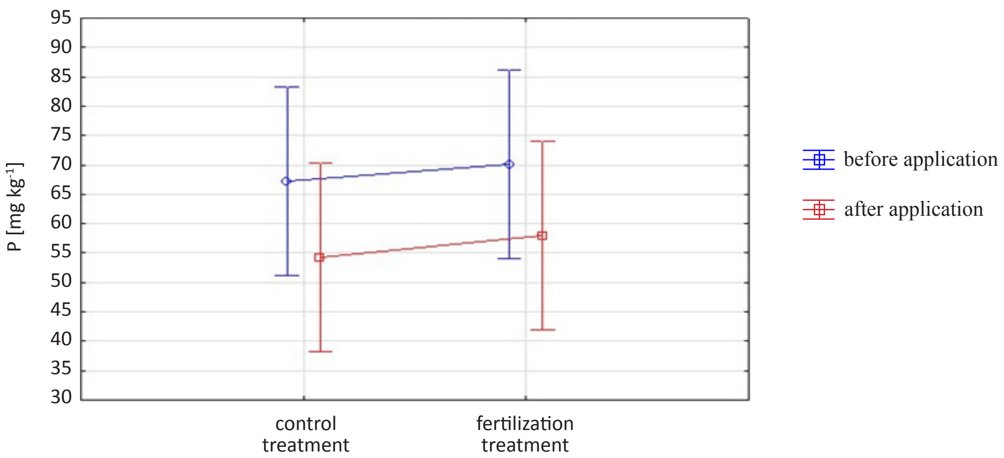

Figure 1. Effect of bottom sediment application on content of available phosphorus in soil.

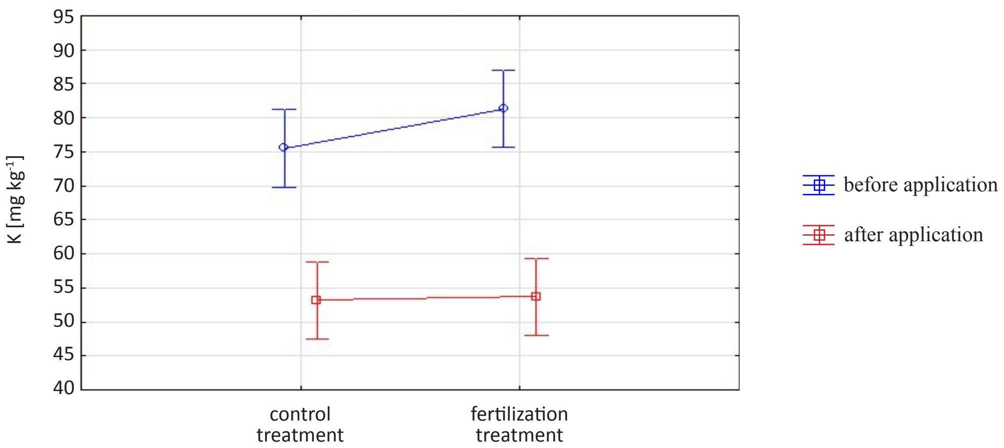

Figure 2. Effect of bottom sediment application on the content of potassium available in soil.

of a bottom sediment caused a 40% fall in the content of available potassium in the soil compared to the untreated control. The reduction in the content of available forms of phosphorus and potassium in the soil samples collected after harvesting the plants from plots that were not subject to fertilization resulted from these elements having been absorbed by plants. No mineral fertilization was used in the cultivation of oats, which is why the plants satisfied their nutritional needs by resorting to soil reserves. Many authors point to the depletion of soil reserves with regard to nutritional elements in the absence of fertilization (Sądej, Mazur, 2005; Mazur, Mazur 2015; Stępień et al., 2005).

Meanwhile, a reduction in the content of available forms of these elements in the soils of those plots in which the bottom sediment was applied may indicate that these elements are present in combinations that are difficult to be accessed by plants and that they are not of considerable significance in terms of meeting the nutritional demands of plants during the first year of applying the sediment. Rahman et al. (2004) and Rahman and Yakupitiyage (2006) have demonstrated similar correlations in their research.

The average content of available magnesium in the soil did not change significantly in control plots (it decreased by 7%), however, it did increase significantly (by 16%) in the plots where the bottom sediment was applied (Table 3, Fig. 3). The increase in the content of available magnesium in soils fertilized with bottom sediment was related to the high content of this element in the sediment and the small nutritional requirements of oats with regard to magnesium. There are no publications directly indicating the positive influence of using a bottom sediment on the content of available magnesium in the soil, although there are many reports on the content of magnesium in bottom sediments (Baran et al., 2013; Gałka, Wiatkowski, 2010; Tarnawski et al., 2012; Dąbkowski, Pawłat-Zawrzykraj, 2003; Rafałowska, Sobczyńska-Wójcik, 2014). What is emphasized in the reports by the above-mentioned authors is the possibility of using sediments as valuable fertilizers due to their content of macroelements, including magnesium.

The impact of the bottom sediment on the content of exchangeable aluminium in the soil and soil reaction

Prior to applying the bottom sediment, the content of exchangeable aluminium in the soil varied and ranged between 5.17 and 56.27 mg kg^{-1} (Table 4), which was likely related to the natural variability of the soil in the field.

After harvesting the plants (August 2016), the content of exchangeable aluminium in the soil decreased significantly in comparison to its content before establishing the experiment (November 2015), both in the control and sediment-treated plots (Table 4, Fig. 4). The average content of exchangeable aluminium in the soil of control plots fell by almost fourfold, while in the plots where the bottom sediment was applied, the value was as much as eight times lower. Oats is a crop that is resistant to acidification and the

Table 4. Content of exchangeable aluminum in soil [mg kg^{-1}] depending on date of soil sampling.

Treatment	November 2015	August 2016
K1	25.60	8.92
K2	5.17	3.22
K3	48.22	9.62
Średnia; Mean	26.33 aB	7.25 bA
O1	13.55	1.35
O2	7.27	0.62
O3	56.27	7.47
Średnia; Mean	25.70 aB	3.15 aA

K – control treatment; O – treatment fertilized with bottom sediment
Small letters (a, b) denote significant differences between the means of treatments, and large letters (A, B) denote significant differences between the means of individual dates.

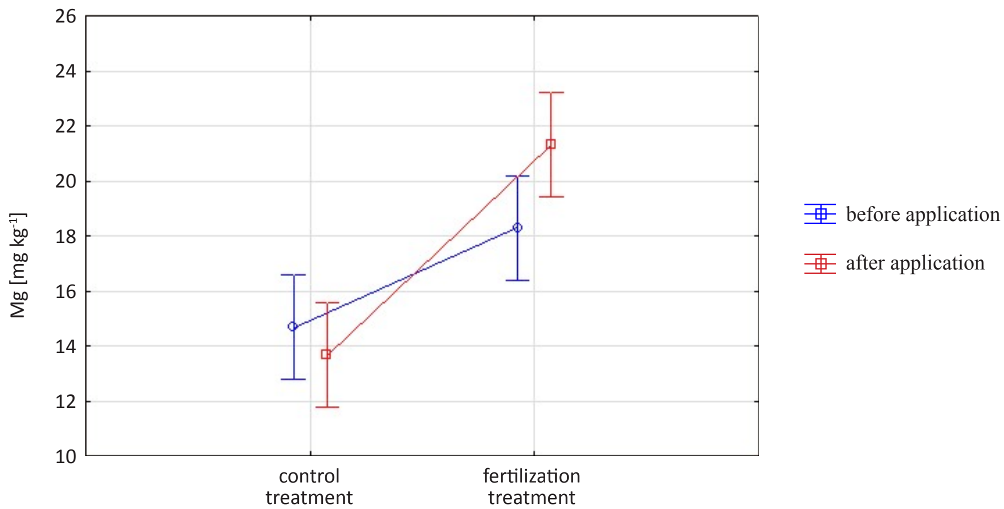

Figure 3. Effect of bottom sediment application on available magnesium content in soil.

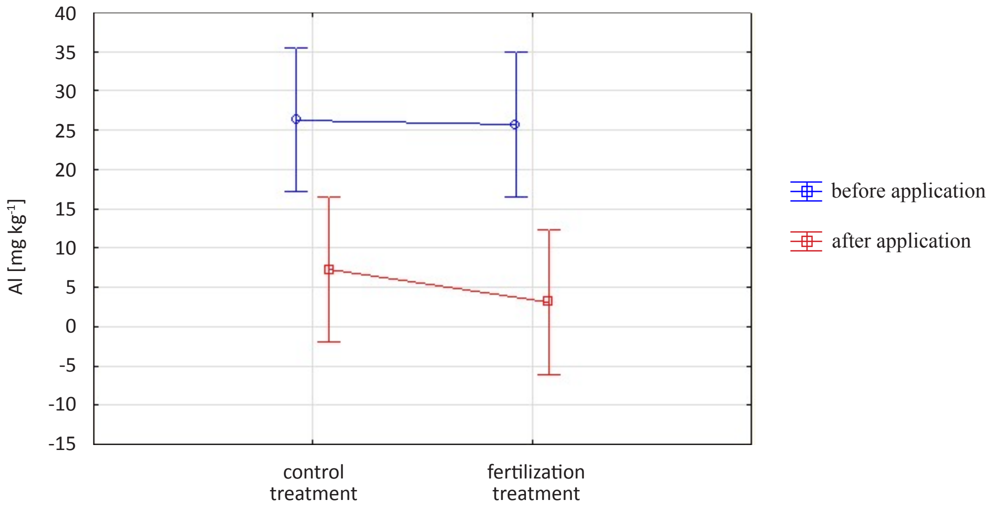

Figure 4. Effect of bottom sediment application on content of exchangeable aluminum in soil.

toxic effects of aluminium. One of the reasons for the observed decrease in the content of exchangeable aluminium in the soil immediately after harvesting the plants might have been the immobilization of this element by organic acids (malic and citric acids), characterized by their ability to chelate aluminium ions released into the rhizosphere by oat roots (Skrzypik et al., 2009).

The reason for such a significant decrease in the content of exchangeable aluminium in the plots where the bottom sediment was used may have been the fact that bottom sediments contain large amounts of organic carbon (Gałka, Wiatkowski, 2010). In riverbed sediments, the content of organic matter may reach 10%; over 10% in dam reservoirs, while in fish ponds, it might reach as much as 25% (Madeyski, 1998). The organic matter located in a bottom sediment demonstrates the ability to form persistent compounds with aluminium, which limits its availability to plants, similarly to applying manure (Huges et al., 1990; Stępień et al., 2002; Rutkowska et al., 2006).

The application of the bottom sediment also had an influence on changes in soil reaction. Slight changes in soil reaction have been found in control stands between the year 2015 and 2016. However, in the plots where the bottom sediment was applied, the reaction of the soil determined after harvesting oats increased by 0.2–0.5 of a unit compared to 2015 (Table 5, Fig. 5).

The increase in the reaction of the soil fertilized using the bottom sediment was caused by the introduction of a highly alkaline material into the soil. The reaction of the tested bottom sediment was neutral (pH = 6.70). Many authors indicate that bottom sediments have deacidifying properties, as they are usually characterized by an alkaline reaction, good sorption and buffer capacities. Therefore, they may be used on light and acidic soils to improve their physical and chemical properties (Arasimowicz et al., 2011; Ciesielczuk et al., 2011; Baran et al., 2011; Rahman et al., 2004; Rahman, Yakupitiyage, 2006).

Table 5. Soil pH depending on date of soil sampling and bottom sediment application.

Treatment	November 2015	August 2016
K1	4.30 a	4.50 ab
K2	4.80 b	4.40 a
K3	4.20 a	4.10 a
O1	4.50 ab	5.00 b
O2	4.70 b	5.00 b
O3	4.10 a	4.30 a

K – control treatment; O – treatment fertilized with bottom sediment
Values marked with the same letters do not differ significantly.

In order to assess the impact of applying the bottom sediment on the physical and chemical properties of the soil, an analysis of the correlations between the content of exchangeable aluminium, the content of available forms of P, K and Mg, and the reaction of the soil was carried out (Table 6).

Based on the analysis of correlations, the content of available magnesium in the soil of the sediment-treated plots was found to be positively correlated with soil pH and with available potassium and negatively correlated with the content of exchangeable aluminium in the soil the sediment-treated plots, was with soil pH. Simultaneously, it was demonstrated that, along with an increase in the reaction of a soil, the content of available aluminium in the soil decreases significantly (r = -0.65) (Table 6). As shown by many authors, a rise in the concentration of calcium and magnesium ions in a soil solution, as well as an increase in the soil's reaction alleviates the toxic effects of Al^{3+} (Porębska, 1996; Badora, Kozłowska-Strawska, 2011).

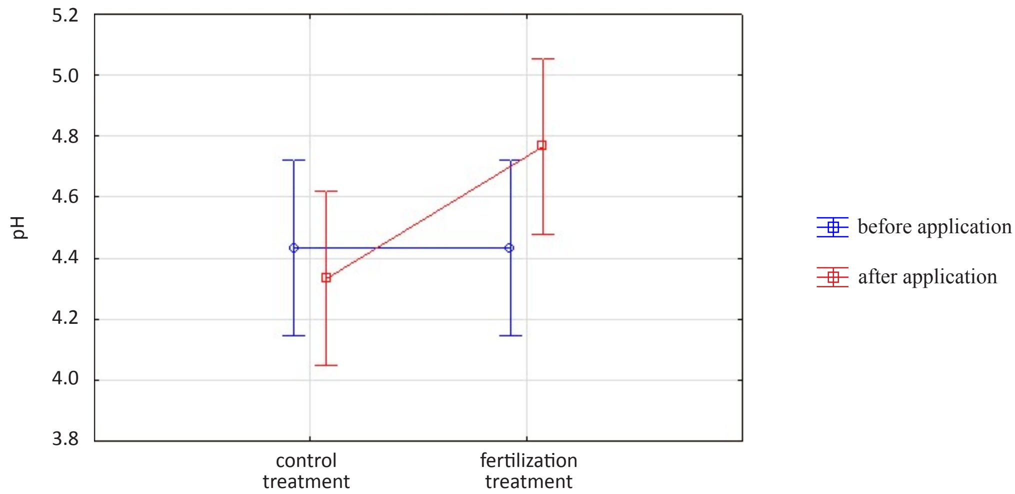

Figure 5. Effect of bottom sediment application on soil $pH_{(KCl)}$.

Table 6. Correlation coefficients between selected soil properties after bottom sediment application.

Variable	Al	P	K	Mg	pH
Al	1.00	0.53*	-0.11	-0.65*	-0.65*
P	0.53*	1.00	-0.14	-0.39	-0.40
K	-0.11	-0.14	1.00	0.68*	0.50*
Mg	-0.65*	-0.39	0.68*	1.00	0.91*
pH	-0.65*	-0.40	0.50*	0.91*	1.00

* statistically significant relationship at $\alpha = 0.05$

To sum up, it might be said that the applied bottom sediment was characterized by a high content of magnesium, which contributed to the increase in the soil's reaction, which, in turn, effected a clear decrease in the content of Al^{3+} in the soil (Table 6, Fig. 4). Although the bottom sediment did not actually increase the yields of oats, it may be used for agricultural purposes chiefly because of its very low content of heavy metals and a beneficial effect on the properties of the soil.

CONCLUSIONS

1. The use of a bottom sediment contributed to reducing the content of exchangeable aluminium in the soil. A statistical analysis of the results indicated that the above was due to an increase in the soil's reaction after the bottom sediment was applied.
2. The bottom sediment had a significant impact on the increase in the soil pH and on the content of available magnesium in the soil.
3. No impact of the bottom sediment was found with regard to the content of available forms of phosphorus and potassium in the soil as well as on the yields of oats.
4. No excess in the permissible content of heavy metals was found in the bottom sediment, therefore, it may be used for agricultural purposes.

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received – 21 October 2018
revised – 21 December 2018
accepted – 7 January 2019

Ministerstwo Nauki i Szkolnictwa Wyższego

„Przetłumaczenie na język angielski wybranych prac zgłoszonych do Polish Journal of Agronomy” – zadanie finansowane w ramach umowy Nr 692/P-DUN/2018 ze środków Ministra Nauki i Szkolnictwa Wyższego przeznaczonych na działalność upowszechniającą naukę