RESEARCH ARTICLE

Effect of bottom sediments on the nutrient and metal concentration in macrophytes of river-lake systems

Angela Kuriata-Potasznik[1,*], Sławomir Szymczyk[1] and Dorota Pilejczyk[2]

[1] Department of Water Resources, Climatology and Environmental Management, University of Warmia and Mazury in Olsztyn, Plac Łódzki 2, Olsztyn 10-719, Poland
[2] Department of Agricultural Chemistry and Environmental Protection, University of Warmia and Mazury in Olsztyn, ul. Oczapowskiego 8, Olsztyn 10-719, Poland

Abstract – Water bodies of river-lake systems can act as barriers in the movement of nutrients and toxic heavy metals outside their water catchment area. These components can be suspended in the water column, deposited in bottom sediments or bioaccumulated by the vegetation in the water body. A constant exchange of substances takes place between bottom sediments and macrophytes. The composition of bottom sediments and their distribution affects the intensity of nutrients and metals assimilation by macrophytes in the river-lake systems. The aim of research was to analyse the effect of bottom sediments on the nutrients and metal content in macrophytes. It was demonstrated that tissues of plants anchored in sediments that were more abundant in nutrients had higher contents of biogenic components and heavy metals. The properties of bottom sediments, mainly their granulometric composition, but also organic matter content and pH, determine the content of biogenes and heavy metals in macrophytes to a significant extent. On the other hand, it was demonstrated that aquatic plants could affect the grain size in the sediments. Macrophytes and sediments of river-lake systems play a very important role in reducing the transport of nutrients outside the area of the system, through capturing and incorporating them into the tissues of aquatic plants.

Keywords: macrophytes / river-lake system / bottom sediments / heavy metal / nutrient

1 Introduction

River-lake systems create chains of lakes connected by rivers flowing through the water body. Water bodies situated along the river course can act as barriers to the matter entering them (and for its transformation or accumulation) or accumulate matter flowing into them from the neighbouring areas or transport matter out along the river (Glińska-Lewczuk, 2005, 2006). The progress in degradation of river-lake systems is demonstrated by an increase in the water trophic status (Potasznik and Szymczyk, 2016). Water bodies functioning in river-lake systems, unlike holding water bodies, are characterized by varied morphology and various trophic states in individual parts of the water body, which leads to their uneven degradation (Duarte and Kalff, 1988). The use of macrophytes to evaluate the degradation of the ecological condition permits determining the correlation between the biotope quality and the quality of biocenos in surface waters. Biomonitoring permits estimating the quality of surface waters in lakes, based on the existence of specific species of plant communities, their range and ability to accumulate nutrients and heavy metals (Duarte and Kalff, 1988).

Macrophytes, being hydrophilic plants, make up an element of rush and swamp systems fulfilling different functions in the environment, for instance:
- they are characterized by a high ability to assimilate biogenic elements and provide a habitat for living organisms (Wang *et al.*, 2013); their assimilative abilities are comparable with the abilities of wetlands (Huang *et al.*, 2015). Such species as *Phragmites australis* and *Typha latifolia* make the vertical substrate for a wide group of organisms, with all trophic levels (producers, decomposers and consumers) (Obolewski, 2005). Reeds are more resistant to overgrowth than bulrush (Obolewski, 2002). This phenomenon is determined by the availability of light, temperature, waves, the type of substrate and the water quality (Obolewski *et al.*, 2011);
- their species composition can reflect the degree of the water body eutrophication and can affect the development of environmental conditions, regulating the intensity of light reaching the water body or species composition of its fauna

*Corresponding author: angela.potasznik@uwm.edu.pl

(Carvalho *et al.*, 2015). Reeds demonstrate high potential to improve water quality (Lakatos *et al.*, 1999). This is a species that is most resistant to varied environmental conditions and which occurs commonly all over the world (Du *et al.*, 2006);

– they also affect the accessibility of oxygen in surface and interstitial water through the processes of photosynthesis, respiration and decomposition (Huang *et al.*, 2015);
– their presence affects the metabolism in bottom sediments (Wang *et al.*, 2013), organic matter content and oxygen release from sediments (Wang *et al.*, 2013);
– their underground parts play a stabilizing function for substrate layers situated near the surface and take up nutrients from sediments located at the bottom (Jin *et al.*, 2016);
– macrophytes are rooted in the bottom, but they are also present in the entire water column, rising above the water surface in the littoral zone (Li *et al.*, 2014);
– they play an important role in the ecosystem structure and participate in cleaning the water in shallow lakes (Yu *et al.*, 2015).

On the other hand, bottom sediments are also responsible for the circulation of elements in the ecosystem (Czamara and Czamara, 2008) and their specific properties determine occurrence of particular species of aquatic plants (Szmeja, 2006). The structure of bottom sediments can be a factor preventing the development of submerged macrophytes (Szafran, 2003). The growth of rush plants depends, among others, on the abundance of bottom sediments in macro- and micro-components (Pachuta and Oglęcki, 2001). Plants take up those components from water and sediments and those accumulated at the bottom can be picked up and suspended in the water depth as a result of the re-suspension process. This process is determined by the sediment structure. Water movement more easily picks up small diameter particles (Parsons *et al.*, 2017). Additionally, the process can be affected by the redox potential of the sediments, oxygen content at the very bottom, temperature, type of chemical compounds and the level of sediment hydration (Bartoszek, 2007). Depending on the fertility of the substrate and its chemical composition, plants of various types can occur and some of those species are characterized by a broad tolerance for those factors (Wesołowski et al., 2001; Pełchaty and Promin, 2015).

The research hypothesis assumes that assimilation of nutrients and heavy metals by individual species of aquatic plants found in river-lake systems was affected mainly by the properties of bottom sediments, such as their granulometric composition, organic matter content and pH. The aim of the research was to analyse the effect of bottom sediments on the content of nutrients and metals in macrophytes. This paper analysed the effect of specific properties of bottom sediments, *i.e.* granulometric composition, organic matter content and pH, on accumulation of biogenes and heavy metals by specific types of aquatic plants in the river-lake system.

2 Methodology

The research was carried out in Lake Symsar, a flow-through lake with an area of 135.5 ha and a maximum depth of 9.4 m (mean 4.7 m) situated in the Olsztyn Lake district in north-eastern Poland. The water body is of the postglacial origin (finger lake). The water body from the south is entered by the Symsarna River, which flows from Lake Luterskie, then through Lakes Ławki and Blanki and leaves the water body analysed in this study, flowing in a northward direction. The course of the river flow divides the lake to into the main body of water, including its southern, western and central parts, and the bay part, situated in its northern most area (Fig. 1), beyond the main course of the river flow. The water catchment area of the lake is covered with agricultural land and forest areas, the western part of the water body features forests, with recreation areas developed with numerous holiday cottages and a beach in the northern part. Therefore, due to a differentiated water catchment area, the water body has been divided into two additional zones: a forest and recreation zone. Rush vegetation occupied about 11.8% of the entire water body coverage and the mean range of the plant occurrence was three metres. In terms of the Ecological State Macrophyte Index applied in biomonitoring as one of the biological indicators of water quality, based on the occurrence of rush vegetation, the lake was assessed as class III lake (WIOS, 2012). Six types of macrophytes were identified in the rush vegetation of Lake Symsar.

For the study purposes, conducted in 2014 in June, 12 representative shoreline belts were selected (30 m wide each) (Fig. 2), their amounts were calculated on the basis of the result of the actual number of profiles (NPA) formula for lakes with surfaces above 20 ha, or the minimum required number of transects (Jensen, 1979; Kolada and Ciecierska, 2009). Transects were located in characteristic places of the water body, such as the presence of recreation areas (points 1, 2, Fig. 2); a lake bay outside the impact area of the river flowing through the water body (3–5); the outlet of the river from the lake (6, 7); the inflow of the main river to the water body and a smaller water course supplied by household sewage (8–10) and the presence of forest areas (11, 12). In each of them (12 transects), all macrophyte species composition were analysed, along with the percentage coverage of the shoreline and, additionally, representative samples of the plants (stems and immersed leaves) occupying an area of about 50 cm^2 were collected in order to perform physico-chemical analyses. To carry out a chemical analysis, the plant material was analysed in three replications. Samples of macrophytes (2 g) were weighed at air temperature and mineralized in Kjeldahl flasks, in heating blocks in an open system. In order to determine total nitrogen, samples were mineralized using a mixture of 95% sulphurous acid p.a. grade manufactured by CHEMPUR, and 30% hydrogen peroxide p.a. grade manufactured by STAN-LAB. The residue obtained was distilled against $0.1 \, mol \, L^{-1}$ HCl in distillation equipment manufactured by BŰCHI and the distillate was titrated with $0.1 \, mol \, L^{-1}$ NaOH. In order to analyse the content of total phosphorus (TP), calcium and magnesium, mineralisation of samples involved the use of a mixture (1:1, v:v) of 65% nitric acid p.a. grade by CHEMPUR and 70% perchloric acid p.a. grade by STAN-LAB and the samples were mineralized at about 120 °C. The residue after mineralization was transferred through a solid filter (type 390) to 500 mL measuring flasks and the filtrate was filled up with distilled water.

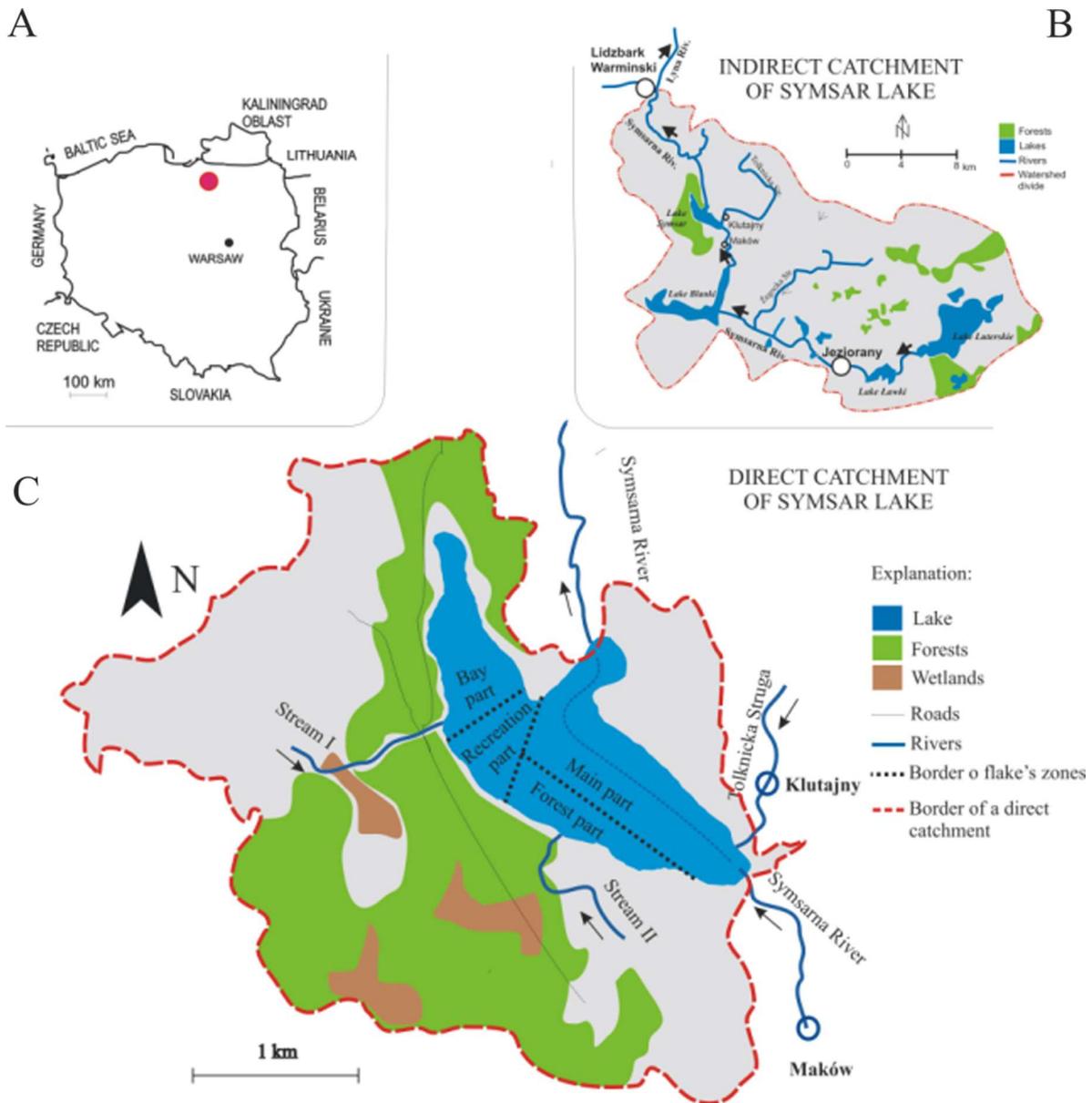The content of TP was determined using the colorimetric method, with ammonium molybdate and tin (II) chloride using

Figure 1. Location of Lake Symsar on the map of Poland (A), use of indirect water catchment area of Lake Symsar (B), use of the direct water catchment area, and the division of the water body into zones.

a spectrophotometer at 650 nm wave length. The content of magnesium oxide (MgO) and calcium oxide (CaO) was determined by titration with 0.01 M disodium dihydrate ($C_{10}H_{14}N_2O_8Na_2$) in the presence of eriochrome black and murexide. The content of Mg and Ca was expressed in mg kg^{-1} s.m. by multiplication by 0.603 (in case of Mg) and by 0.715 (in case of Ca). Mineralization of samples to determine heavy metals was carried out as in the case of TP against the mixture of nitric and perchloric acids at 200 °C. The analysis of a blind sample and of certified reference materials was prepared with the same reagents. About 1 mL residue after distillation (milky deposit and transparent residue over the deposit) was transferred to a solid filter (type 390) to 500 mL measuring flasks and filled up with distilled water. Concentrations of available zinc (Zn), manganese (Mn), iron (Fe), chromium (Cr), copper (Cu), nickel (Ni), cadmium (Cd) and

lead (Pb) were determined in three replications in the laboratory of the Chair of Chemistry and Environmental Management of the University of Warmia and Mazury in Olsztyn, using the atomic absorption spectrophotometer (AAS-6800 Schimadzu) in an air-acetylene system. The BGC-D2 (deuterium background correction) was used. External standards were used to ensure analytical quality control. A peak search was performed in the vicinity of the expected analytical lines: Mn − 279.5 nm, Cr − 357.9 nm, Cu − 324.8 nm, Ni − 232.0 nm, Cd − 228.8 nm, Pb − 217.0 nm, Zn − 139 nm. The results of the analyses of the certified reference material CRM055-50G (Sewage Sludge Certified Reference Material specified by the ISO Guides 34, 35 and ISO 17025, SIGMA–ALDRICH) were as follows: 693 mg Mn kg^{-1}, 289 mg Cr kg^{-1}, 482 mg Cu kg^{-1}, 163 mg Ni kg^{-1}, 60.6 mg Cd kg^{-1}, 154 mg Pb kg^{-1} and 1240 mg Zn kg^{-1}. The results of blind tests were as
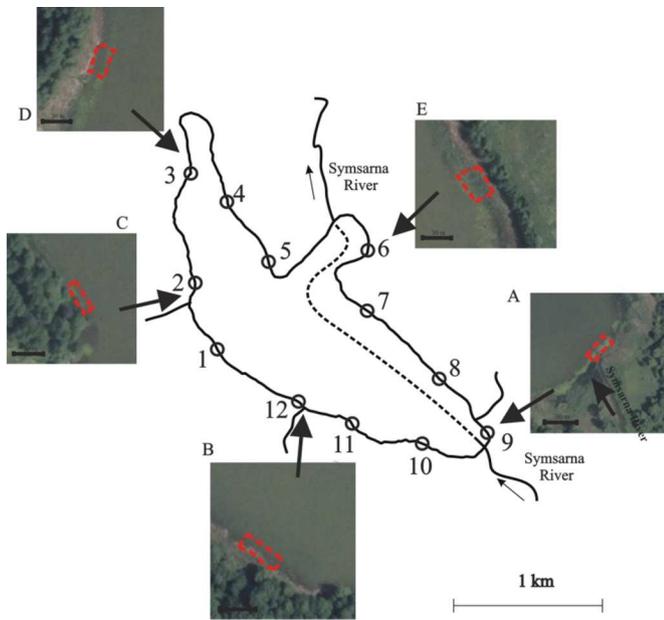
Figure 2. The location of representative 30-m belts of macrophytes in Lake Symsar and the range of selected transects (A, B, C, D, E).

follows: 677.5 mgMn kg^{-1} (97.8%), 310.7 mgCr kg^{-1} (107.3%), 503.3 mgCu kg^{-1} (104.4%), 174.9 mgNi kg^{-1} (107.3%), 63.1 mgCd kg^{-1} (104.0%), 152.54 mgPb kg^{-1} (8.1%) and 1076.2 mgZn kg^{-1} (86.8%) and all of them were within the acceptable range of deviation. Samples of bottom sediments (13 points) were collected from representative places of the water body, at the depth of 0–10 cm, with the use of the Ekman grab. Air-dried sediments were ground in a mortar and analyzed to determine the physicochemical parameters such as organic matter content (OM, g kg^{-1}), by the gravimetric method, after drying at 105 °C and incinerating in a muffle furnace at 550 °C; and pH, by the potentiometric method in KCl (actual and exchangeable acidity), 1:2.5 (w/v) ratio.

The significance of differences in component accumulation of macrophytes between different parts of the lake was assessed with a non-parametric analysis of variance: Kruskal–Wallis' test (K–W, $p \leq 0.05$) followed by Dunn's test as a post hoc procedure. Correlations between fractions, organic matter content (OM), pH and heavy metal contents were assessed with the r-Pearson correlation analysis. The response of the component content in macrophytes to the environmental conditions was analyzed using multivariate statistical analyses. Detrended correspondence analysis (DCA) and redundancy analysis (RDA) (Canoco 4.5 software package) (Ter Braak and Smilauer, 2002) were used for analyses of macrophyte abundance. DCA was used first to determine the character of variability in the studied assemblages: the length of the first gradient is greater than two standard deviations − unimodel variations, smaller than two SD − linear variations. The results of DCA indicated linear variations, providing justification for the future use of RDA. RDA was used to obtain an overview of the community level statistical significance of the canonical axes determined using a Monte Carlo permutation test. The environmental factors under analysis included: (a) location of macrophytes in the water body, with reference to the division

of the examined water body into zones, (b) macrophytes species: *Typha latifolia* L., *P. australis*, *Nymphaea alba* L., *Myriophyllum spicatum*, *Equisetum fluviatile* L., *Typha angustifolia* L, (c) bottom sediment properties: granulometric content (fraction: medium sand, fine sand, very fine sand, clay, silt), pH and organic matter content.

3 Results

Macrophytes growing along the course of the Symsarna River and near the beach, *i.e.* in the recreational part, contained the highest amounts of total nitrogen and its phytosorption was as follows: main part>recreational part>bay>forest. In the recreational part, rushes also accumulated phosphorus (by 39.8% more in comparison to other zones): recreational part>bay>forest>main part (Tab. 1). Plants in the lake bay contained the highest amounts of calcium, a Eurasian water milfoil was observed in this zone, which prefers waters rich in calcium: bay>recreational>forest>main part. On the other hand, magnesium was prevailing in plants in the forest part and also in the bay part: forest>bay>recreational>main part.

The results of the Kruskal–Wallis test and the post-hoc test demonstrated a significant difference of lead and zinc content between plants growing in different location in the water body. The results of Dunn's test showed a statistically significant difference in lead concentration between plants growing in the bay part and the forest part (Tab. 1). A high concentration of these metals was observed in rushes of the lake bay located in the western part of the water body, near the southwest-north communication route.

In tissues of common reed, *P. australis*, the most frequent plant in the water body, performed mainly cadmium, while in other plant species under analysis the concentrations of this metal was below the level of determination (Tab. 2). As regards heavy metals in tissues of the reedmace, *Typha latifolia* L., high concentrations of nickel and chromium were observed. As it has already been mentioned, it grew mainly in the bay part. On the basis of the research conducted, it was found that the common water lily plants, *N. alba* L., demonstrated a high ability to absorb nitrogen and phosphorus, while in the tissues of Eurasian water milfoily, *M. spicatum*, performed mainly calcium and magnesium and, as regards metals, also copper, nickel, chromium, zinc and manganese. In tissues of reedmace, *Typha angustifolia* L., were observed mainly high concentrations of lead. On the other hand, the horsetail, *E. fluviatile* L., occurring at the shore covered by the forest, concentrations of calcium and magnesium were highest than in tissues of other species, but also nitrogen and, as far as metals are concerned, manganese (Tab. 2).

The RDA was carried out on the basis of the nutrient content in macrophytes of the tested water body, *i.e.* total nitrogen, TP, calcium and magnesium, the content of heavy metals: cadmium, copper, lead, nickel, chromium, zinc, manganese and environmental variables, *i.e.* the location of plants in the water body, their species and properties of bottom sediments: fraction, pH and organic matter (Figs. 3 and 4). The RDA analysis (Figs. 3 and 4, Tab. 3) showed that component content in macrophytes was highly correlated with the first components (axis 1–46.2% of value). On the other hand, the second axis showed moderately low correlation (2.7% of

Table 1. The concentration of individual components: nutrient and metal [g kg^{-1}], organic matter [%] and granulometric fraction [%] with reference to the location of macrophytes in the water body.

Zone	N$_K$	P	Ca	Mg	Mn	Ni	Cr	Cd
Recreational	67.66	0.84	35.01	5.67	0.52	0.015	0.002	<
Bay	50.00	0.74	79.44	11.92	0.59	0.018	0.003	0.0003
Main	68.79	0.48	22.68	4.66	0.44	0.012	0.004	0.0003
Forest	40.84	0.58	54.88	16.94	0.29	0.001	0.001	<
P	0.053	0.151	0.301	0.875	0.270	0.060	0.066	0.150

Zone	Cu	Zn	Pb	OM	Medium sand	Fine sand	Very fine sand	Clay, silt
Recreational	0.0016	**0.015**	0.0005	15.70	36.18	17.67	10.65	35.50
Bay	0.0024	0.013	**0.0196**	16.28	39.10	15.38	7.44	38.09
Main	0.0019	0.013	0.0062	17.88	36.84	16.56	11.23	35.37
Forest	0.0020	**0.004**	**0.000**	17.97	38.14	13.36	17.86	30.64
p	0.708	0.046*	0.010*					

Table 2. Concentration of individual components [g kg^{-1}] by species of plants in Lake Symsar.

Species	N$_K$	P	Ca	Mg	Mn	Ni	Cr	Cd	Cu	Zn	Pb
Typha latifolia L.	68.96	0.47	27.92	4.42	0.55	0.024	0.0032	<	0.0025	0.019	0.010
Phragmites austalis	54.50	0.70	22.77	2.79	0.32	0.007	0.0034	0.0002	0.0013	0.008	0.002
Nymhaea alba L.	86.00	1.02	43.09	11.09	0.51	0.003	0.0010	<	0.0009	0.013	0.000
Myriophyllum spicatum	42.22	0.87	237.24	42.77	1.19	0.024	0.0039	<	0.0042	0.020	0.006
Typha angustifolia L.	39.26	0.73	44.83	0.79	0.54	0.023	0.0036	<	0.0033	0.010	0.015
Equisetum fluviatile L.	43.45	0.66	95.83	33.09	0.41	0.003	0.0014	<	0.0016	0.005	0.000
p	0.414	0.439	0.795	0.128	0.169	0.253	0.690	0.546	0.351	0.196	0.234

Denotations: n = 18, p – results of Kruskal–Wallis test,< – value below detection limits.

value). On the basis of the RDA, a close relationship is observed between the clay, silt content in sediments and the total nitrogen concentration in tissues of rush plants, particularly in the bay zone and along the course of the Symsarna River. Fractions of very fine and medium sand were correlated with pH of sediments and the organic matter content. Lead and zinc were reversely correlated with plant location in the water body with high contents of the examined components present in tissues of the bay plants (Fig. 3). A comprehensive tool in the description of relationship between contents of analysis components (species and environmental variables) is RDA with forward selections with Monte Carlo permutation test. Based on analysis of gradients related to first and second components, one may conclude that the variance explained between concentrations of nutrients, metals and environmental variables is high and amounts to 74.4% and 56.4%, respectively. The relations are the strongest between location and Cd, Cr and Pb content in macrophytes (Fig. 3). Cadmium and chromium were prevailing in zones within the reach of the Symsarna River and the bay (Fig. 3, Tab. 1), mainly in tissues of *P. australis*, most abundantly occurring in those zones. On the other hand, lead was present mainly in the bay part, where its content observed in plant tissues was eight times higher than in any other zone (Fig. 3, Tab. 1). Additionally, an environmental factor, such as the species,

demonstrated a similar gradient in relation to calcium (Fig. 4); this component was present mainly in the tissues of *M. spicatum* (with almost five times higher content than in tissues of other plants, Tab. 2).

The RDA carried out for the most frequent species in the examined river-lake water body: *P. australis* and *Typha latifolia*, demonstrated that the concentrations of components, *i.e.* phosphorus and chromium in tissues of *P. australis* was closely correlated with the fraction of sediments (phosphorus with the finest fraction, *i.e.* clay, silt) while chromium was closely correlated with the largest fraction − medium sand.

4 Discussion

In this study, the research conducted concerned the bioaccumulation of nutrients and metals in aquatic plant in river-lake system as an effect of properties of bottom sediments.

The accumulation of metals in this species could depend, among others, on the type of the water ecosystem, but also on habitat conditions of macrophytes (Obolewski *et al.*, 2011). In the studies conducted, a organic matter content in bottom sediments possibly affecting on the concentration of nutrients and metals in reed tissues (for example the zinc content) and fraction of sediments was correlated with the concentrations of
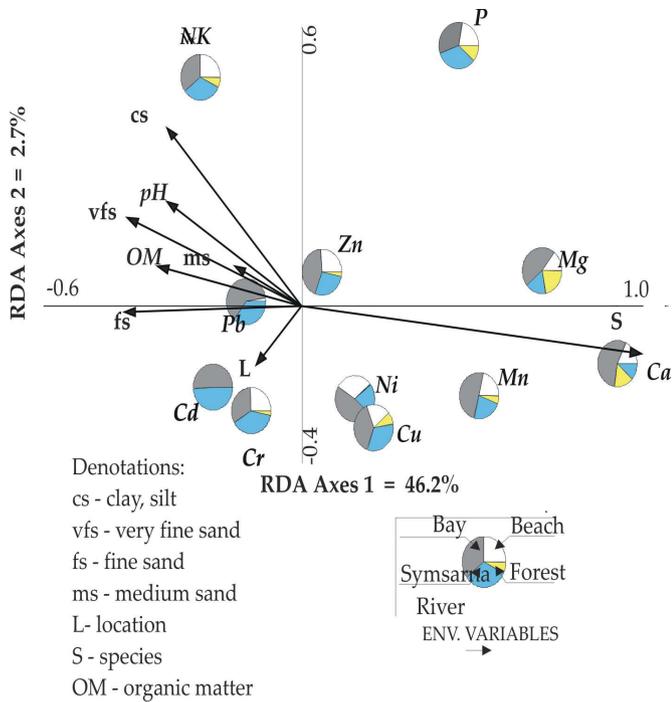
Figure 3. Ordination plot of Redundancy analysis (RDA) for component content (species) and location, macrophytes species and bottom sediments properties: pH, OM and fraction (environmental variables). Relative value of components contents in pie classes represented by the location in lake zone.
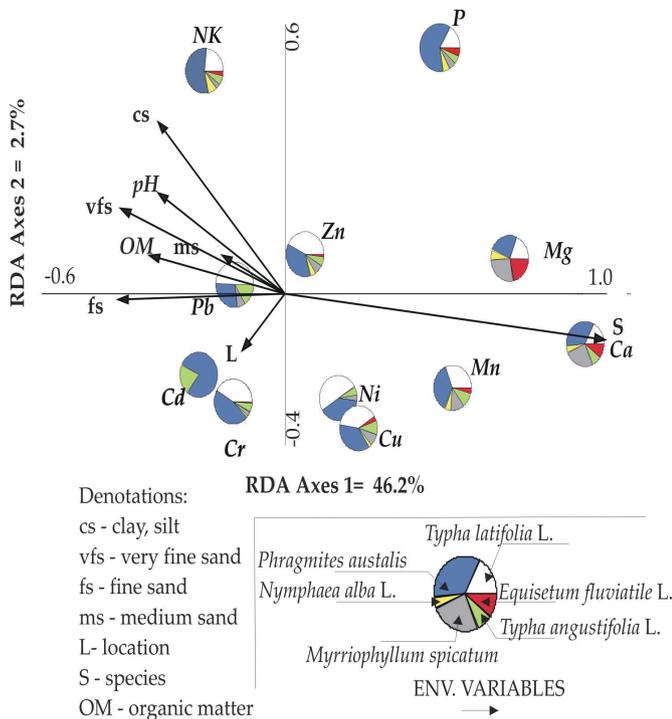

Figure 4. Ordination plot of Redundancy analysis (RDA) for component concentration (species) and location, macrophytes species and bottom sediments properties: pH, OM and fraction (environmental variables). Relative value of components contents in pie classes represented by species of macrophytes.

Table 3. Results of ordination plot of Redundancy analysis (RDA).

Axes	1	2	Total variance
Eigenvalues	0.462	0.027	1.000
Species-environment correlations	0.744	0.564	
Cumulative percentage variance			
Of species data	46.2	48.9	
Of species-environment relation	91.1	96.4	
Sum of all eigenvalues			1.000
Sum of all canonical eigenvalues			0.507

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chromium and phosphorus. The nickel content in its tissues depended on the fraction of sediments on which its plants grew, which were most frequently the finest ones. Most components are accumulated in its roots with less in rhizomes, stems and leaves (Sasmaz *et al.*, 2008).

The uptake of substances, including metals, by the plant depends on the bioavailability of the components in water and in sediments which, in turn, depends on the metal retention time (Branković *et al.*, 2012). The compound content in tissues of aquatic plants is quite often determined by the development of the water catchment area (biogenes and metals are carried away from the catchment area, accumulate in sediments and from there, they are assimilated by roots of aquatic plants). The presence of the communication route (municipal hard-surfaced road) not only contributed to lead accumulation in sediments neighbouring on the route (Kuriata-Potasznik *et al.*, 2016), but also to its accumulation by nearby rushes, which was even five times higher than in rushes of other zones (particularly the species of *Typha angustifolia* and *latifolia*). Based on the results reported by Kuriata-Potasznik *et al.* (2016) and the results obtained in this paper, it can be concluded that plants anchored in sediments with lower levels of biogenic compounds will be characterized by lower contents of biogenic compounds in tissues. However, aquatic plants can accumulate high concentrations of toxic metals, to levels exceeding the norms for soil or sediments (Branković *et al.*, 2012). According to Skorbiłowicz *et al.* (2016), the content of heavy metals in plant tissues reflects the content of metals in sediments. In turn, according to Duarte and Kalff (1988), morphometrical characteristics of water bodies, *i.e.* depth, exposure to wind and waves and inclination of the bottom, seem to have a greater effect on the growth of submerged macrophytes than the level of nutrients in sediments. In a study by Kisson *et al.* (2013), the impact of two factors on the growth of macrophytes was emphasized: the organic matter content and the size of particles in bottom sediments. The studies demonstrated a relationship between macrophytes and distribution, composition and size of sediment particles in the water environment. They are thought to play an important role in stabilization of sediments and reduce the re-suspension of sediments, bottom erosion and water turbidity. At low depths, when macrophytes occupy the entire water column, water flow intensity is reduced. At greater depths, when the water level is higher than the maximum height of the plant canopy, wave suppression is limited and the substances are suspended in water. The transport of larger particles of sediments requires higher flow rates, which are reduced by the

presence of aquatic plant habitats. In such a case, the particles are deposited at the bottom and the growth of plants on a coarse substrate is significantly impeded (Madsen *et al.*, 2001). Very fine particles are also difficult to erode and those fractions are characterized by the ability to retain nutrients (Kisson *et al.*, 2013), which are assimilated by plants, resulting in their more intensive growth (Madsen *et al.*, 2001). Kuriata-Potasznik *et al.* (2016) found that the content of such metals as cadmium and chromium in sediments was correlated with the presence of the fine sand fraction in those sediments. In this paper, the content of those metals was related to the location of rushes and their higher concentrations were most frequent in plants of the main part, where, according to Kuriata-Potasznik *et al.* (2016), very fine fractions were prevalent. In the river-lake system, near the outlet of the river into the lake, deposition of coarse fractions, such as medium sand, are observed. Along with the distance from the outlet, the strength of the water current permits transporting the carried material further on, where finer fractions are deposited (Kuriata-Potasznik *et al.*, 2016). Outside the range of rush plants, in the bottom sediments of the profundal zone of the water body, very fine fractions of dust and loam are prevailing (Kuriata-Potasznik *et al.*, 2016).

The finest fraction, *i.e.* silt and clay, was related to the nitrogen content in plant tissues. In the longer-term perspective, constant accumulation and deposition of particles may result in water opacity or shadowing of the photosynthetic surfaces, which can reduce plant growth. Additionally, plants are also nourished by nutrient transport through cracks in sediment particles, mainly sands and gravels (Madsen *et al.*, 2001).

The effects of organic amendments in heavy metal bioavailability depend on the nature of the organic matter, their microbial degradability, salt, pH and redox potential, and also type of metals (Ganesh *et al.*, 2015). Metals also have high affinity for humic, organoleptic, and organic oxides (Connell and Miller, 1984). Metal formed complexes with hydrated iron and manganese oxides, as well as with organic matter (Zerbe *et al.*, 1999). The content of nutrients and heavy metals in sediments is dependent from organic matter decomposition, the principal role belongs submersed and floating rooted plant (Pajević *et al.*, 2003). An increased share of organic matter in sediments is the effect of anaerobic decomposition resulting from a high level of methanogenes and methane saturation in interstitial water (Jespersen *et al.*, 1998). Organic substances accumulate more frequently in the vicinity of macrophyte habitats than in sediments of open waters. Constant accumulation of matter is not a favourable condition for plants. According to Koch (2001) and Madsen *et al.* (2001) even more than 5% content of organic matter can lead to plant death. The sediments in the examined water body of the river-lake system contained up to 15.9% organic matter in the recreational part and up to 17.9% in the forest part (Kuriata-Potasznik *et al.*, 2016). Disturbances in the sediment structure through resuspension seems to have a favourable effect on plants, since it reduces decomposition of matter.

Species of aquatic plants differ between each other in their anatomy, physiology, tolerance of stressors, such as flow rate, light, salinity, ice cover, temperature, content of nutrients, competitiveness and diseases. Many species adjusted to the stress factors and reveal an ability to adapt to difficult environmental conditions (Lacoul and Freedman, 2006). In the river-lake system of the lake district landscape, the Eurasian water milfoil, *M. spicatum*, occurring in waters of the bay, is a species which, which is adapted to the conditions of excessive calcium concentration. The presence of this species in the bay zone was correlated with the bottom sediment abundance of this component (Potasznik and Szymczyk, 2015).

Fluctuations in the water level play a significant role in regulating the growth of macrophytes. Water depth is one of the most important factors determining the division into zones, distribution and spatial arrangement of the reed, *P. australis*, tolerant to long-term flooding (Tóth, 2016). In the research object, this species occurred most often in all zones of the river-lake water body covered by plants, often occupying the entire area of the examined transects (ranging from 60 to 100%). The reed is a species present in rushes of water ecosystems for long periods, semi-permanently or temporarily and rhizomes of those plants contribute to decomposition of organic and inorganic matter (Meyerson *et al.*, 2016). In almost the entire water body, the common reed *P. australis* occurred as a typical species representing swamp and water plants, with a wide ecological tolerance range. Its range in individual transects covered from 60 to 100% of the surface. The reedmace, *Typha latifolia* L., a characteristic species for the shores of still and slow-moving waters, growing on the muddy substrate, abundant in organic matter, was also very frequent. Its presence accounted for about 10% coverage of the area. Additionally, the lesser reedmace, *Typha angustifolia* L., was also present in the bay part. As with the reedmace, it is a species typical for still or slow-moving water, growing on loamy or sandy ground. In Lake Symsar, it was present in its eastern part, featuring large land denivelations. In addition, the Eurasian water milfoil, *M. spicatum*, a species that is free-floating or anchored on the bottom and typical for waters rich in calcium, was present in the bay part. In the recreational part, near the beach, the small water lily *N. alba* L., was found, which is a protected species, growing in shallow still waters up to two meters deep with sandy and silty bottom, *i.e.* typical for littoral zones of water bodies. The forest part featured the swamp horsetail *Equisetum fluviafile* L., typical for rushes located in the vicinity of forests.

P. australis transports oxygen through its stalks to its rhizomes and roots, and then to the zone of sediments around the root resulting an oxidized microenvironment in the rooting and contributing to loosening of the substrate structure by root overgrowth, which increases the coefficient of filtration, while a lower density of sediments makes them a good sorbent. Oxygen diffusion and oxygen access to the roots are affected by less densification. Under anaerobic conditions deposits become a major source of phosphorus. Additionally, roots act as biocatalysts, permitting the optimum growth of microorganisms in the ground and water zone, after which the components taken up by the plant are built into its cells (Todorovics *et al.*, 2005). In turn, *Typha latifolia* is a typical invasive species, quickly expanding its range and is capable of creating monospecific habitats, which often displace native species (Selbo and Snow, 2004). Additionally, the literature emphasizes the role of this species as an effective protective barrier for bottom sediments and water (Parzych *et al.*, 2016). Nutrients and metals taken up by the aquatic plants are accumulated in their roots, stems and leaves. The species demonstrates a high ability to assimilate

heavy metals, with tolerance to their increased concentrations without severe physiological damage. The bioaccumulation rate in plants can depend on the species and environmental load (Shafi *et al.*, 2015).

The presence of some species of plants can be correlated not only with morphometric conditions, *i.e.* depth, but also the abundance of nutrients in sediments (Johnson and Ostrofsky, 2004). One example is the Eurasian water-milfoil, which inhabits sediments rich in calcium. The intensity of component removal, including metals, from an aquatic environment depends on pH, redox status and the nature of the contamination (Mishra *et al.*, 2008; Branković *et al.*, 2012). For instance, *Typha* can grow in low pH levels (Brix *et al.*, 2002). In turn, the lead contents in aquatic plants were inversely correlated with the reaction of bottom deposits, where lower pH values determined its higher contents in rushes. Jackson *et al.* (1993) demonstrated that low pH of bottom sediments and mild redox conditions increased bioavailability of some metals by aquatic plants. In our research, this dependency is observed for the nitrogen content in plants. The process of interaction between aquatic plants and sediments consists in oxygen transport through the stalks to rhizomes and roots, which results in the creation of an aerobic zone around the roots. In this zone, as a result of the aerobic bacteria activity, carbon compounds are released, which is followed by the process of ammonium nitrogen nitrification. Outside the roots, in the anaerobic zone, the process of dephosphorization and denitrification occurs. This results in proliferation of microorganisms in the substrate. Oxygen transport to roots results in increasing the aerobic decomposition of organic matter (Brix, 1994).

The accumulation of metals by aquatic plants and in bottom sediments is a response to progressing urbanization (Rzymski et al., 2014). According to Njuguna *et al.* (2017), industrial development, household sewerage, agricultural activity and waste are the factors that contribute to this phenomenon to the largest extent. On the basis of the conducted research, it was observed that plants in specific zones accumulated individual metals with various intensity. In plants occurring along the course of the Symsarna River, the nutrients accumulating in the highest amounts included nitrogen and phosphorus and the metals cadmium and chromium. Similar to research of Kuriata-Potasznik *et al.*, (2016) in the recreational zone, most of the determined components under analysis were accumulated in macrophytes, which resulted from anthropogenic factors, including the inflow of domestic wastewater. The location of macrophytes in the water body may depend on exposure to wind and waves, depth of the water body, water clarity, abundance of nutrients in water and sediments. However, the greatest impact on the abundance of nutrients was found for the type of substrate on which the plants grow. Bottom sediment is an underestimated factor affecting the efficiency of nutrient removal by plants (Tang *et al.*, 2017).

Macrophytes in the water body can transform solar energy reaching the lake ecosystem (Li *et al.*, 2014), as well as metabolize various pollutants suspended in the water column (Wang *et al.*, 2013) through assimilation by aquatic plants (Li *et al.*, 2014). During their growth, plants can accumulate nutrients by direct uptake, but they also can absorb it directly from sediments through their roots anchored in the bottom (Carvalho *et al.*, 2015). The research by Potasznik *et al.* (2014)

suggests that during the period of vegetation involving intensive growth of macrophytes in the water body, nutrient takeout outside the area of the water catchment area is reduced. This shows an environmentally important role of macrophytes which, by retaining some pollution, can reduce its outflow from the drainage area, which can mitigate the negative effects of human activity on water ecosystems (Wang *et al.*, 2014).

5 Conclusion

The greatest effect on the accumulation of an excessive amount of substances like nutrients and heavy metals occurring in the water ecosystem of the river and lake system seems to be demonstrated by properties of the bottom sediments, mainly their granulometric composition, and, to a lower extent, the organic matter content and pH. The granulometric composition of sediments, with the domination of very fine fractions, plays a very important role in stabilising sediments. These sediments create a dense structure, preventing bottom erosion by the water movement. This results in retaining the nutrients at the bottom, and reduces their uptake by the plants. On the other hand, it was demonstrated that aquatic plants can have an effect on the fraction size in sediments, particularly near the outlet of the river to the water body. Since the granulometric composition of sediments in the river-lake system is determined by the river flowing through the lake, it has an indirect effect on assimilation of components from the bottom by aquatic plants.

The river-lake system is a specific trap for biogenes, as due to their accumulation in sediments or aquatic plants, it reduces their penetration outside the system. Identifying factors affecting the assimilation of nutrients by macrophytes, such as the properties of bottom sediments, can permit in the future creating controlled conditions leading to contamination capture, simulating the operation of a river and lake system.

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