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The European beaver *Castor fiber* is well-known as an ecosystem engineer that greatly affects landscape structure, biodiversity as well as physical and chemical properties of surface water bodies. Beaver ponds alter surface water bodies by raising water elevation, decreasing flow velocity and altering the morphology of streams or drainage ditches, which can reduce the concentrations of organic carbon (OC) and nutrients (N, P). Recent studies indicated that mercury transforms into hazardous and neurotoxic methylmercury (MeHg) in beaver impoundments by biological processes in anaerobic conditions.

However, the knowledge about nutrients and MeHg levels in impounded forest waterbodies is scarce in Lithuania. We aimed to ascertain the alteration in concentrations and stocks of OC, nutrients and MeHg in water and sediments from upstream and downstream, as well as within beaver dams and ponds during the growing seasons of 2016–2018. Results showed higher concentrations of dissolved organic carbon (DOC) and nutrients (P and N) in upstream water samples compared to those of downstream from beaver dams. Meanwhile, in sediments mean stocks of OC, P and N were the highest in the middle part of the ponds and in beaver dams. Moreover, the concentrations and stocks of MeHg in sediments were higher in beaver dams than in any other parts of beaver impoundments (upstream, mid-pond, pond periphery and downstream). We conclude that dam bottom sediments were rich in OC, N and P, and at the same time, contained toxic MeHg. Therefore, beaver dams could act as a trickle filter by improving water quality, in our case, DOC, N and P leaching, from riparian forests and soils, but may also act as hotspots of mercury methylation.

Keywords: beaver, dam, impoundment, methylmercury, nitrogen, organic carbon, phosphorus, sediment

The European beaver *Castor fiber* was exterminated within countries located in the Baltic Sea region during the 19th century due to intensive human activities such as forestry, which reduced the carrying capacity of once stable stream systems, and hunting and trapping practices (Nolet and Rosell 1998, Halley et al. 2012). However, the beaver has recently made a remarkable recovery in many European countries due to legal protection and targeted conservation measures, which include hunting restrictions, reintroduction and translocations, natural recolonization, land and water protection, and habitat restoration (Belova et al. 2017). Today, the beaver is again widespread throughout Europe (Busher and Dzięciolowski 1999, Halley et al. 2012, Borowski 2014), however, countries such as Lithuania face challenges in managing beaver population (Belova et al. 2017). While beaver harvesting is strictly controlled and

limited in most European Union (EU) countries, beavers can be hunted and trapped as a game species throughout much of Eurasia, including EU member states as Estonia, Finland, Latvia, Lithuania, Sweden and partly Poland (Belova et al. 2017).

The European beaver is well-known as an ecosystem engineer that markedly affects forest-landscape structure, biodiversity and the physical and chemical properties of surface waterbodies (Bouwes et al. 2016, Puttock et al. 2017, 2018). The beavers impact the hydrological condition of waterbodies by building dams and consequently impound a large amount of water in ponds (Majerova et al. 2015, Puttock et al. 2017, 2018). Ponds raise the surface-water elevation, decrease the flow velocity and alter the morphology of streams or drainage ditches. Organic and mineral particles of soils usually accumulate as the bottom sediments of impounded waterbodies which can cause water chemistry changes (Pollock et al. 2007, 2014, Law et al. 2016, Catalán et al. 2017, Puttock et al. 2018). In addition, several studies reported that beaver pond–dam complexes can act as sediment traps (i.e. cause downstream nitrogen, phosphorus), due to the rapid decrease in velocity when water

enters a pond (Butler and Malanson 1995, Klotz 2007, Puttock et al. 2017).

Furthermore, recent studies also show that beaver ponds can increase methylmercury (MeHg) concentrations within impounded waterbodies (DeMarco 2015, Levanoni et al. 2015, Ortega et al. 2018). In impounded waterbodies, methylation of Hg is favoured by absence of free oxygen and is mediated by bacteria species as *Desulfovibrio desulfuricans* and *Geobacter* sp. (Compeau and Bartha 1985). Moreover, higher concentrations of Hg in soils and sediments may also correspond to the natural properties of the underlying bedrock, especially, regolith (Loukola-Ruskeeniemi et al. 2003). Humic acids may release from soils and may transform dissolved Hg into MeHg (Melamed et al. 2000, Eklöf 2019). Meanwhile, in beaver ponds, MeHg usually is retained in association with bottom sediments (Wängberg et al. 2010, Driscoll et al. 2013, Wiener 2013, Science for Environment Policy 2017, Hsu-Kim et al. 2018). Furthermore, numerous studies reported that phytoplankton absorbs MeHg by passive diffusion, therefore, there is a risk that this contaminant formed in beaver ponds can enter to aquatic food chain (Mason et al. 1996, Moye et al. 2002, Pickhardt and Fisher 2007).

Studies concerned with organic carbon and nutrient composition in beaver impounded water bodies are scarce in Lithuania, and such studies usually were focused on chemical changes of water in upstream and downstream from beaver dams (Lamsodis and Ulevičius 2012a). Furthermore, the concentrations of Hg and MeHg in beaver impounded water bodies were never investigated in Lithuania before. Since the soils in Lithuania consists mainly of sandy and silt loams and are sensitive to erosion. Therefore, it is important to get knowledge about MeHg levels in impounded surface water bodies.

In this study, we monitored alterations in organic carbon (OC), nutrients (N, P), Hg and methylmercury (MeHg) concentrations in water and sediments in three beaver sites. We predicted that beaver ponds and dams may act as a trickle filter that improve downstream water quality.

Our study will provide and expand stakeholder knowledge of beaver dam management considering new approaches for water quality.

Material and methods

Study sites

The study was performed during three growing season periods of 2016–2018 at the forests of northwestern part of Lithuania in beaver-impounded: 1) natural forest stream (56°14′3″N, 21°26′2″E), 2) channelized forest stream (56°10′6″N, 21°27′7″E) and 3) forest drainage ditch (56°14′3″N, 21°26′2″E) (Fig. 1). The natural forest stream was in the area dominated by Scots pine *Pinus sylvestris* (mean stand age – 49 years). The channelized forest stream and forest drainage ditch were in areas dominated by silver birch (*Betula pendula*, mean stand age – 40 years) and Scots pine (mean stand age – 13 years), respectively. The bottom sediments of the studied water bodies were formed from catchment soils: mineral particles and organic matter

Figure 1. Study area in northwestern Lithuania (top panel) whereby three beaver impoundments were sampled (lower panel). The natural forest stream is depicted by an N, channelized forest stream is depicted by a C and the forest drainage ditch is depicted by a D.

comprised 60–90% and 10–40%, respectively (Kadūnas et al. 1999). Elevation across sites varied in the range from 36 m to 49 m a.s.l. The climate in Lithuania is described as semihumid, transitional between maritime and continental (Galvonaitė et al. 2013). During study period (2016–2018) average annual temperature was 5.4°C, and average annual amount of precipitation was 897 mm in study area. After the last Nemunas (Riss-Wurm, Weichselian) glaciation, soils were developed from glacial lacustrine deposits and were classified as Arenosol (found in the adjacent to natural forest stream) and Luvisols (channelized forest stream and forest drainage ditch) (Buivydaitė et al. 2001, WRB 2014 (2015)).

Water sampling and chemical analysis

Water samples (total n = 18) were collected from upstream and downstream locations of each beaver dam at each site in August of each year (Fig. 2). Chemical analyses of water samples were performed in the Agrochemical Research Laboratory of Lithuanian Research Centre for Agriculture and Forestry (LAMMC).

For each water sample we quantified: pH using the potentiometric method (ISO 10523 2008; CyberScan pH 6500 pH meter, Eutech Instruments); dissolved organic carbon (DOC) concentrations using titration method; dissolved total nitrogen (total N) by spectrophotometry method (ISO 11905-1 1997; FIAstar5000, SoFia software);
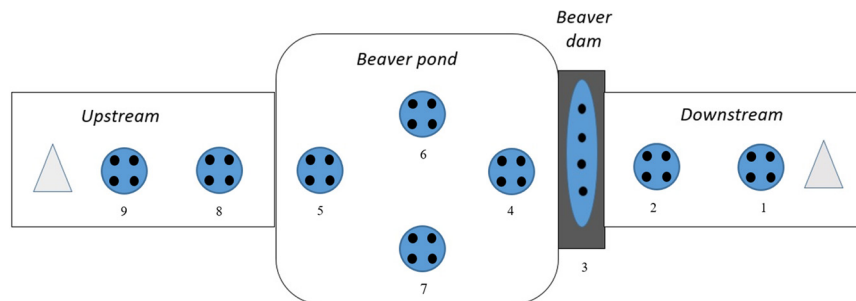
Figure 2. Design of water (△) sampling and sediment composite (⬤) sampling in impounded water body. Sampling locations: 1–2 – downstream, 3 – beaver dam, 4–5 – mid-pond, 6–7 – pond periphery, 8–9 upstream.

total phosphorus (total P) by continuous flow photometry (ISO 6878 2004; Uvmini-1240, Shimadzu Corporation); and mercury (Hg) by atomic absorption spectrometry (ISO 12846 2012; Perkin Elmer FIMS, FIAS 200 software). For DOC titration, 10 ml of water sample was treated with 1 g of $HgSO_4$, $K_2Cr_2O_7$ (0.04 mol l^{-1}) and H_2SO_4 (conc.) and boiled for 2 h. Then solution was titrated with 12 mol l^{-1} moric salt (($NH_4)_2Fe(SO_4) \times 6H_2O$) until the color of solution changed from violet to green (ISO 8245 1999).

Bottom sediment sampling and chemical analysis

Composite samples (consisted of four subsamples; Fig. 2) of the bottom sediment were collected using the vacuum sediment borer (inner diameter – 63 mm; height – 485 mm). At each site, nine composite samples were taken from upstream (n = 2), mid-pond (n = 2), pond-periphery (n = 2), downstream (n = 2) and from the beaver dam (n = 1) (Fig. 2). All collected bottom sediment samples were immediately stored in a sterile polyethylene container and frozen down to −78°C. The frozen bottom sediment samples were lyophilized at the Institute of Horticulture of LAMMC. Organic carbon (OC) content was determined using dry combustion at 900°C with a CNS analyzer (ISO 10694 1995; Elementar Analy-sensysteme GmbH, Germany). Total nitrogen (total N) was determined using the Kjeldahl method (ISO 11261 1995), and total phosphorus (total P) was determined using colorimetric determination (ISO 11466 1995). Methyl mercury (MeHg) was determined using species-specific isotope dilution followed by mass spectrometry. Chemical analysis of OC, total N and P were performed at the Agrochemical Research Centre of LAMMC, while MeHg was determined at the IVL Svenska Miljöinstitutet, Sweden.

The stocks of organic carbon (OC, kg m^{-2}), total N and total P (g m^{-2}) and MeHg (μg m^{-2}) were calculated by multiplying the concentrations with sediment mass.

Statistics

The differences between sampling points for water properties, sediment mass, concentrations and stocks of studied chemical parameters were compared using separate one-way analysis of variance (ANOVA) and Tukey's tests, with a statistical significance at p < 0.05. Meanwhile, there were no differences among three studied sites in distribution of concentrations of TOC ($F_{2,17} = 2.13$, p = 0.27), total N ($F_{2,17} = 4.12$, p = 0.18) and P ($F_{2,17} = 1.07$, p = 0.45) in col-

lected water samples and OC ($F_{2,79} = 0.29$, p = 0.75), total N ($F_{2,79} = 0.48$, p = 0.62) and P ($F_{2,79} = 1.91$, p = 0.17) and MeHg ($F_{2,79} = 0.41$, p = 0.67) in bottom sediment samples.

Results

There were no detectable differences in pH, total P and total Hg in water samples collected in upstream and downstream from beaver dams (p = 0.5, Fig. 3). However, mean concentrations of DOC ($F_{1,17} = 4.91$, p = 0.04) and total N ($F_{1,17} = 10.80$, p = 0.03) were 2.7 times and 44% higher, respectively, in upstream locations of beaver dams.

Mean mass of sediments differed across beaver impoundments ($F_{4,77} = 2.23$, p = 0.009; Fig. 4). The lowest mean mass of sediments was detected upstream (71 ± 10 kg m^{-2}), downstream (84 ± 26 kg m^{-2}) and in pond periphery (98 ± 15 kg m^{-2}). The mean mass of sediments in pond periphery was only by 17% and 38% higher compared with upstream and downstream locations, respectively. However, compared with upstream and downstream locations as well as the pond periphery, mean mass of sediments in beaver dams (280 ± 131 kg m^{-2}) and mid-ponds (254 ± 100 kg m^{-2}) were 4-fold and 3-fold higher, respectively.

In general, mean concentrations of chemical parameters in bottom sediments decreased in the order: OC > total N > total P and, undoubtedly > MeHg (Fig. 5). Mean concentrations of OC varied from 19 g kg^{-1} to 38 g kg^{-1} across beaver impoundments ($F_{4,77} = 6.93$, p = 0.001). The lowest mean concentration of OC was determined downstream of beaver dams. Compared with downstream, mean concentrations of OC were on average 70% higher in the mid-ponds and at beaver dams.

Mean concentrations of total N varied from 1.25 g kg^{-1} to 5.45 g kg^{-1} ($F_{4,77} = 6.56$, p = 0.001) and total P varied from 247 mg kg^{-1} to 619 mg kg^{-1} ($F_{4,77} = 7.75$, p = 0.001) (Fig. 5). Mentioned concentrations of nutrients had similar trends with the highest levels being upstream (by 3.0–4.5-fold for total N and 2.2–2.5 times for total P) and second highest levels were detected in mid-pond by 1.7–2.0 times (for both N and P).

Mean concentrations of MeHg in bottom sediments ranged between 0.3 and 2.9 ng g^{-1} across beaver impoundments ($F_{4,77} = 5.25$, p = 0.004; Fig. 5). The highest mean concentration of MeHg was found in beaver dams. Compared with beaver dams, the mean concentration of MeHg was 3-fold lower in pond periphery and 7–9-fold lower in

pH

DOC

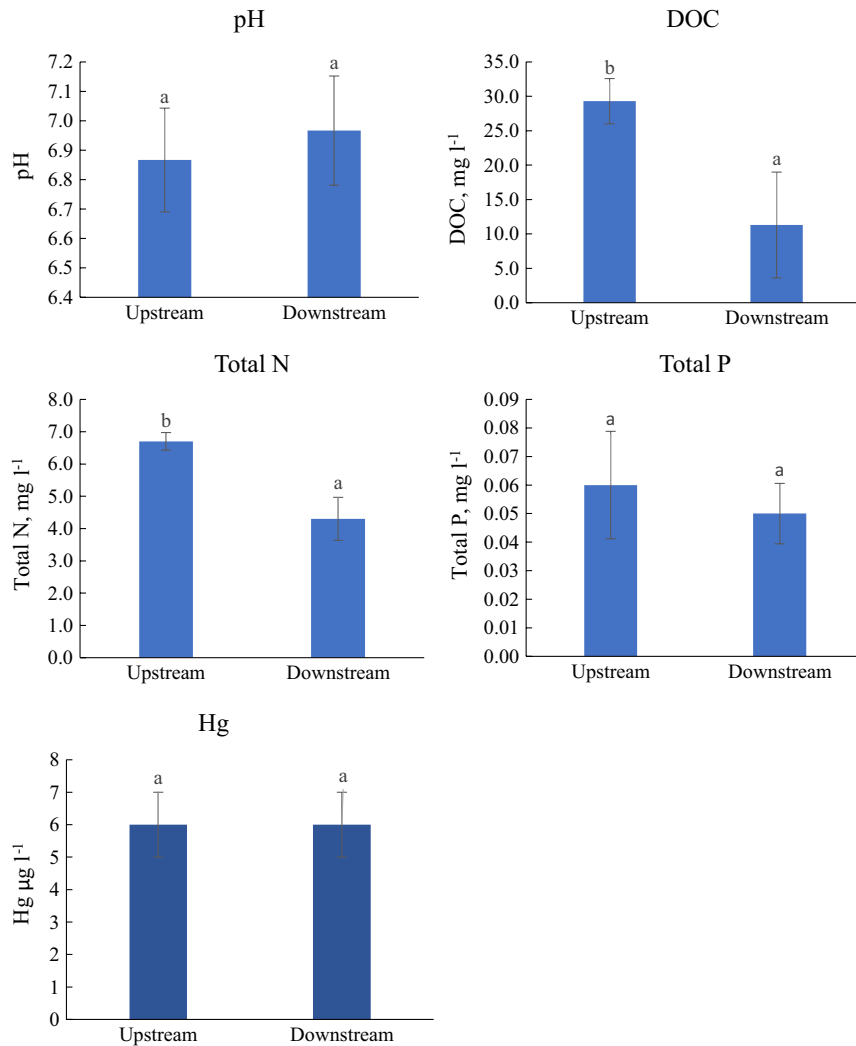## Total N

Total P

Hg

Figure 3. Mean pH values and mean concentrations of dissolved organic carbon (DOC), total nitrogen (total N), total phosphorus (total P) and mercury (Hg) in water samples in upstream and downstream locations of beaver dams in summers of 2016–2018. The results are expressed as the mean ± SE (total number of samples n = 18; in sampling site: 9 samples were taken upstream and 9 downstream). Different lower-case letters indicate significant differences at p < 0.05.

downstream, mid-pond and upstream locations of beaver sites, respectively.

The highest mean stocks of OC (ranging from 5.0 kg m^{-2} to 9.0 kg m^{-2}) ($F_{4,77} = 2.561$, p = 0.049) and total N (343–625 g m^{-2}) ($F_{4,77} = 2.50$, p = 0.049) were accumulated upstream, in the mid-ponds and at the beaver dams (Fig. 6). Mean OC stocks were 2–4-fold lower, and total N stocks were 2–5-fold lower as well at ponds periphery and downstream.

Meanwhile, mean stocks of total P were highly variable and ranged from 21 g m^{-2} to 210 g m^{-2}, especially in beaver dams and mid-ponds. However, the highest mean stocks of total P (103 ± 43 g m^{-2}) ($F_{4,22} = 1.973$, p = 0.134) were determined in the mid-ponds, while the intermediate mean stocks of total P (43 ± 7 g m^{-2}) were found upstream of the beaver dams. The lowest total P stocks by 2–5-fold were determined in the periphery of ponds and downstream from the beaver dams.

Moreover, the highest mean MeHg stocks (ranging from 223 µg m^{-2} to 513 µg m^{-2}) were at beaver dams ($F_{4,77} = 8.38$,

p = 0.001; Fig. 6). Compared with beaver dams, MeHg stocks were 3 times lower at the periphery of the ponds, 7-fold lower in the mid-ponds and 17-fold lower upstream of and downstream from the beaver dams.

Discussion

We provide new information on organic carbon and nutrients distributions, and mercury methylation in aquatic environments created by beavers. The dams they build to provide ponds with stable water levels and create water-quality-boosting wetlands. In this process, beaver dams slow water velocity and filter out suspended solids, and consequently beaver ponds as natural wetlands positively affect reducing transport excess of dissolved organic carbon (DOC) and nutrients (total N and total P) to downstream of surface-water bodies (Lamsodis and Ulevičius 2012a, b, Gibbs 2014, Pipkin 2015). For example, Gibbs (2014) showed that sediments in beaver ponds contained notable higher concentrations of
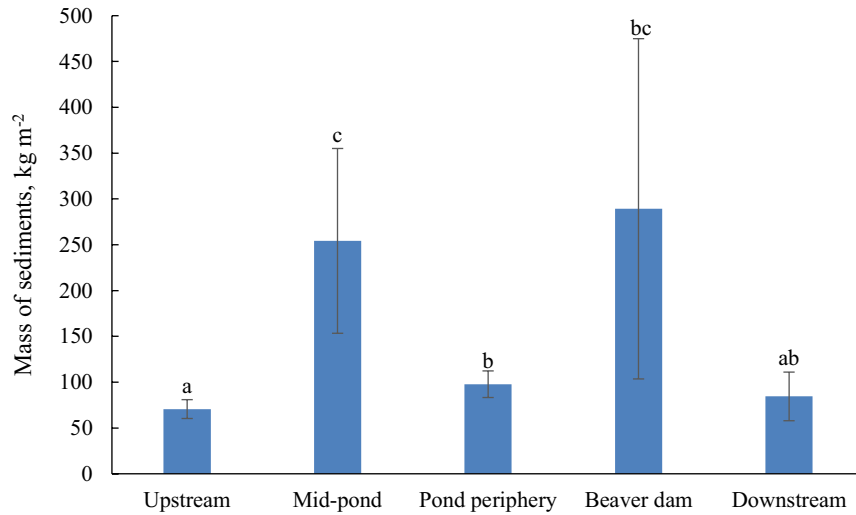
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Figure 4. Mean mass of bottom sediments in studied beaver sites in summer (2016–2018). The results are expressed as the mean ± SE (total number of samples n = 81, in sampling site: 18 samples were taken upstream; 18 – in the mid-pond; 18 – in periphery of beaver pond; 9 – beaver dam; 18 – downstream). Different lower-case letters indicate significant differences at p < 0.05.

organic carbon (OC), phosphate and nitrate than sediments from upstream and downstream locations of beaver dams.

Our study confirmed above mentioned findings, since the highest stocks of OC, total N and total P were accumulated in the sediments at the mid-ponds and beaver dams. As a consequence, the mean concentrations of DOC were decreased by 3 times, total N by 60%, and total P – by 20% in downstream water. Therefore, beaver dams are associated with protective ecosystem service as they reduce the excess of nutrients in stream water, leading to subsequent reduced nutrient loads to estuarine and coastal waters (Como and Deegan 2015).

However, beaver ponds do have some negative effects as they could increase methylmercury (MeHg) in surface waterbodies (Roy et al. 2009, DeMarco 2015, Levanoni et al. 2015, Ecke et al. 2017, Ortega et al. 2018). For example, studies carried out in Canada (Roy et al. 2009) and Sweden (Ortega et al. 2018) reported that beaver impoundments create suitable conditions for MeHg formation because of low stream flow and thick sediment layer that is rich in the organic carbon. The results of our study showed that MeHg concentrations did not differ in upstream and downstream water. However, MeHg concentrations and stocks significantly increased in beaver dam
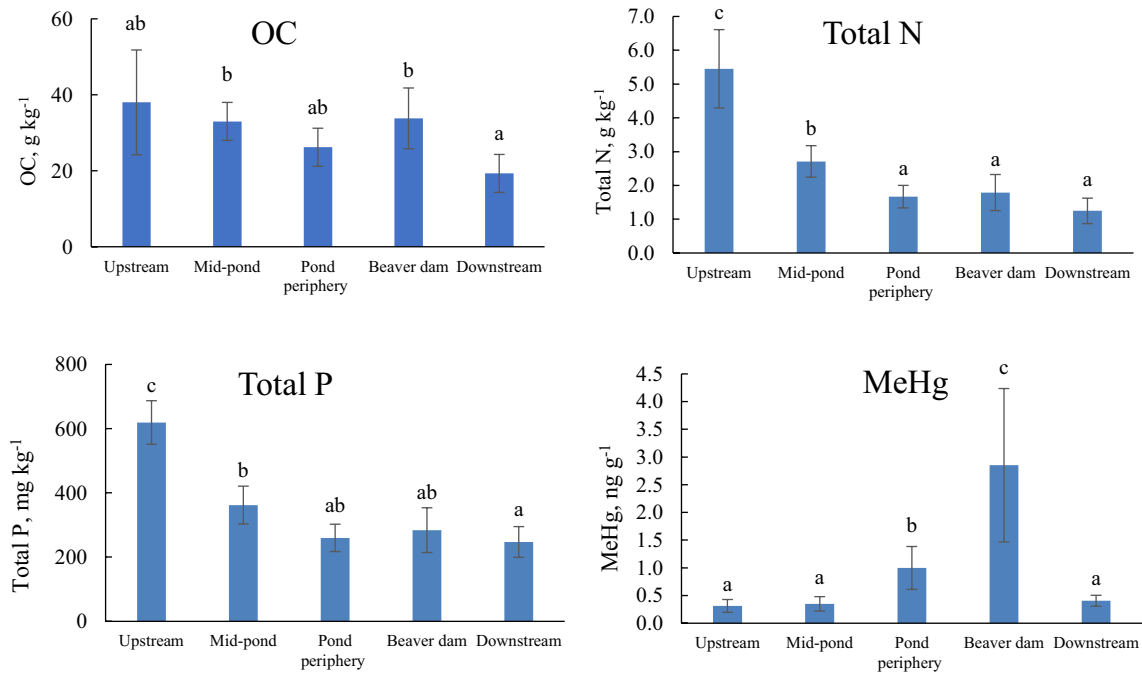

Figure 5. Mean concentrations of organic carbon (OC), nutrients (total N and total P) and methyl mercury (MeHg) in bottom sediments of studied beaver sites in summers of 2016–2018. The results are expressed as the mean ± SE. Notes: total number of samples see in Fig. 4. Different lower-case letters indicate significant differences at p < 0.05.

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OC stocks

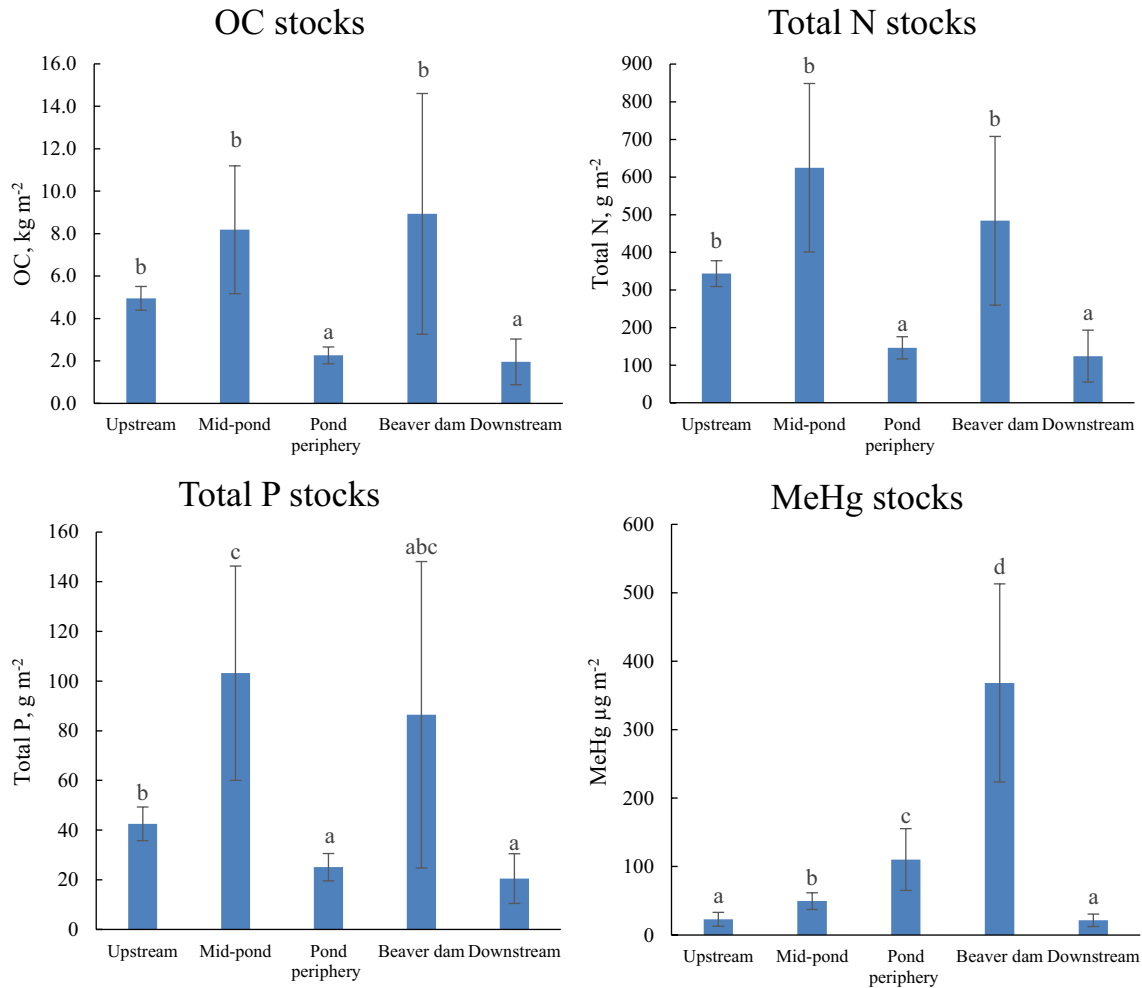## Total N stocks

Total P stocks

MeHg stocks

Figure 6. Mean stocks of organic carbon (OC), nutrients (total N and total P) and methyl mercury (MeHg) at bottom sediments in studied beaver sites in summers of 2016–2018. The results are expressed as the mean ± SE. Notes: total number of samples see in Fig. 4. Different lower-case letters indicate significant differences at $p < 0.05$.

sediments in comparison with sediments of other parts of beaver impoundments. Bigham et al. (2017) reviewed studies concerned with MeHg concentrations in sediments and reported that these sediments can be a potential source of MeHg for biota. Bełdowski et al. (2009) determined that MeHg is labile compound and it can be released from sediments and transported to waters. Furthermore, Painter et al. (2015) found that MeHg concentration in predatory invertebrates found downstream of beaver pond increased up to 1.7 times. Therefore, there is a risk that bioavailable MeHg formed in beaver dams or ponds can enter the aquatic food chain. However, further research will be required to understand how much MeHg could be accumulated in aquatic biota.

Our hypothesis that beaver dams can act as trickle filter was therefore partly confirmed. We found that beaver dams could control loads of biogenic substances to surface-water bodies, and, at the same time, could act as hotspots of Hg methylation.

The beaver is still under special protection across Europe according to a meaningful of international legal acts (i. e. Council Directive 92/43/EEC on the Conservation of Natural Habitats and of Wild Fauna and Flora) and in the

Appendix III of the Bern Convention. Numerous studies confirmed that despite impoundments causing MeHg formation, the beavers play other crucial role including maintenance of biodiversity, increase landscape heterogeneity, improve water quality and could reduce the negative impact of summer draughts as well (Naiman et al. 1994, Como and Deegan 2015, Belova et al. 2017, Rozhkova-Timina et al. 2018). However, landowners suffer significant economic losses if productive forests and agricultural areas are flooded (Härkönen 1999). Furthermore, as in recent studies our findings confirmed that beaver dams and ponds create favorable conditions for the formation of MeHg. Therefore, there is a need to find an optimal solution for adaptive beaver management. The beaver dam management could include the complex of measures as: 1) dissemination of information about beaver positiveness and negative effects, and hunting/trapping depending on the beaver population density; 2) implementation of protective measures (water outlets, fences, tree protection, dam removal and etc.); 3) economic impacts and beneficial effects on biodiversity and water quality. Moreover, our results encourage further studies on management opportunities to lessen MeHg levels in order to protect living beings.

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