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Sediment trapping – An attempt to monitor temporal variation of microplastic flux rates in aquatic systems☆

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ABSTRACT

Sediment trapping as a tool to monitor microplastic influx was tested in an urban boreal lake basin. The one-year-long trap monitoring consisted of 5-month and 7-month periods representing growing season and winter season (including the spring flood event), respectively. Sediment accumulation rate (SAR), and organic content were determined, highest SAR – 14.5 g/m^2/d – was measured during the winter period. Microplastics were extracted from the sediment applying heavy-liquid density separation method and collected under a microscope for further identification with FTIR spectroscopy. PE was identified as the most abundant synthetic polymer type, while PP and PET are also present. The annual microplastic flux rate is 32 400 pieces/m^2/year, and highest accumulation does not coincide with the highest SAR, but occurs during the growing season. Changes in the microplastic accumulation rates are related to seasonal conditions. Highest microplastic concentration with respect to dry sediment weight (10 200 pieces/kg) was observed in a growing season sample, while highest concentration with respect to sediment volume (1800 pieces/l) was observed during winter. This finding underlines the problems related to reporting microplastic concentrations in various units. The results highlight that sediment trap monitoring is an efficient tool for monitoring microplastic accumulation rate in aquatic environments and provides an opportunity to better understand and define processes controlling microplastic accumulation.

1. Introduction

The enrichment of plastic litter in aquatic environments (GESAMP, 2016) causes potential risks for environment, economy and health (EU, 2010). Microplastics are defined as small, < 5 mm plastic particles (GESAMP, 2016) and divided into primary microplastics, which are manufactured to small size, and secondary microplastics, which are fragmented from larger plastic items. Plastic is chemically inert and therefore generally persistent material. It can, however, fragment to microplastics via chemical and physical degradation caused, for example, by abrasion and ultraviolet (UV) radiation (Andrady, 2011; O'Brine and Thompson, 2010). Therefore, microplastics are persistent pollutants in aquatic ecosystems, where they become enriched to sediments, remain preserved for a long time and cause ecological risks (Wang et al., 2019).

Recent research has revealed the frequent occurrence of microplastics in aquatic environments, in rivers (Campanale et al., 2020; Mai et al., 2019; Mani et al., 2015; McCormick et al., 2016), urban to remote lakes (Eriksen et al., 2013; Free et al., 2014; Uurasjärvi et al., 2020), and oceans (Baini et al., 2018; Gewert et al., 2017; Kanhai et al., 2017; Lusher et al., 2015). Microplastics have also been reported from lacustrine (Ballent et al., 2016; Zhang et al., 2016) and marine sediments from coasts (Alomar et al., 2016;

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Claessens et al., 2013; Reed et al., 2018) to deep basins (Bergmann et al., 2017; Van Cauwenberghe et al., 2013). However, due to a large variation in composition and properties of the sedimentary material and accumulation rates, as well as the variety of applied sampling and analysis methods (Hidalgo-Ruz et al., 2012; Rocha-Santos and Duarte, 2015) the reported microplastic measurements are not spatially or temporally comparable. Additionally, the rates of microplastic burial into sediments remain largely unknown (Bancone et al., 2020).

Detailed temporal measurements of microplastic flux rates are needed for investigating the accumulation rate of microplastics in different environments and for understanding the change in microplastic concentrations through time. Long-term observations reveal the rate and direction of change in microplastic flux rate with respect to sediment influx. This type of information is crucial for modelling microplastic accumulation in the future, performing risk assessments, and estimating the influence and effectivity of implemented conservation methods.

Sediment traps are widely used to quantify seasonal sedimentation cycles and sediment components (Ojala et al., 2013) to identify sediment sources and controls on sedimentary processes (Johansson et al., 2019), and to measure sediment accumulation rates (SAR). Thus far, only few attempts have been made to measuring microplastic accumulation using sediment trap monitoring (Ballent et al., 2016; Enders et al., 2019) even if understanding accumulation and transport processes (Waldschläger and Schüttrumpf, 2019) and quantifying the microplastic accumulation rate is identified as one of the critical steps in microplastic studies (Bancone et al., 2020; Enders et al., 2019). In addition to microplastic flux rate (Enders et al., 2019), sediment trapping could potentially provide more detailed information on microplastic sources, and processes controlling the fate of microplastic in water bodies as well as on the seasonal changes in microplastic input – seasonality being a factor that is known to largely control accumulation rate and composition of natural sediments.

We used a classic sedimentological tool, sediment trap, set on the lake floor of Huruslahti Bay in Lake Haukivesi (Eastern Finland) basin to test sediment trapping as a tool to measure annual flux rate of microplastic accumulation in the sediments as pieces m^{-2} day^{-1}. The aim of this study was to develop a monitoring method that enables accurate estimation of microplastic fluxes from catchment to the aquatic system and measures the efficiency of interventions. Moreover, sediment trapping increases the understanding of microplastic burial rates in relation to seasonal sediment cycle and provides information on sources and fate of microplastics.

2. Materials and methods

2.1. Study site

Huruslahti Bay is a closed bay in the larger Lake Haukivesi basin (Fig. 1). The areal extent of the Huruslahti Bay is 1.9 km^2 and the maximum water depth is 11 m. An inlet flows into the basin from the Northwestern end, and two out-flows drain into the main Haukivesi basin from the Southeastern part of the bay. The bay is surrounded by the municipality of Varkaus that has a population of approximately 21 000 people.

A regional source for the microplastics is the City of Varkaus with its urban areas surrounding the Huruslahti Bay. A potential "hotspot source" for microplastics at the Huruslahti Bay shore is a factory, in which plastic has been separated from used liquid packaging board and cardboard as a part of recycling processes during the past years. Today, up to thousands of tons of municipal plastic waste are stored, treated and co-incinerated in energy boilers in this industrial area each year.

2.2. Sampling - sediment trap

The sediment trap consists of a signal buoy, flotation buoys, directing wing, anchor weight and the two collector tubes with bottom weights that keep the tubes in an upright position at all times. The collector tubes are connected to the metal trap body with an articulation to ensure the upright position of the collector tubes regardless of currents or movement while lifting the sediment trap. The collector tubes are made of polymethyl methacrylate (PMMA) plastic for durability, light weight and unbreakable structure, while the tube bottom is made of stainless steel. The tube volume is 1.7 l, height 51 cm and the inner diameter 6.6 cm.

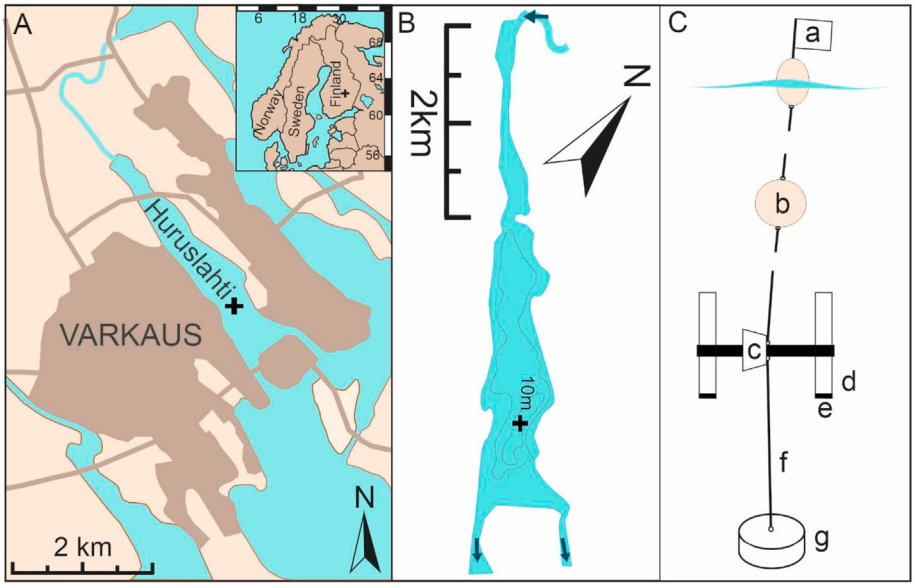

Fig. 1. Study site is marked with a cross. A) Huruslahti Bay in the municipality of Varkaus (dark). B) Bathymetric map of Huruslahti bay. C) Configuration of the sediment trap used in Huruslahti Bay: a = Signal buoy, b = flotation buoy, c = directing wing, d = collector tube, e = tube bottom weight, f = rope, g = anchor weight.

Sediment trap was installed on the lake bottom of the deepest part of the basin from a boat on 4th of June 2017. A 3-L PVC signal buoy was submerged at the depth of approximately 3 m to prevent disturbance by boat traffic or ice cover. Sinking polyester ropes were used for connecting the trap to the signal buoy and the anchor. The sediment samples representing growing season (GS) were collected on 23rd of October 2017. The trap was lifted up carefully using a drag. The sample material (water and sediment) was collected into 3-L plastic containers and the collector tubes were rinsed into the containers with distilled water to ensure recovery of all the sediment material. The containers were sealed with tape and labelled. The collector tubes were then re-installed on the sediment trap, which was instantly lowered to the same location at the lake bottom very carefully to avoid disturbing the soft surface sediments. The samples representing winter season (WS) were collected on 27th of May 2018 in a similar manner.

2.3. Sample processing

2.3.1. Determination of sediment properties

The first collector tube was used for investigating sediment properties. Sediment volume was measured using a measuring glass with 24-h settling time. Organic matter content was measured following the method by Heiri et al. (2001). Excess water was decanted and sediment samples were dried in an oven at 105 °C for 24 h, cooled in a desiccator and weighed. A subsample of approximately 0.2 g was weighed and combusted at 550 °C for 4 h for determining the organic matter content of the samples. Combusted samples were cooled in the desiccator and weighed. Minerogenic matter content was obtained by subtracting loss on ignition (LOI) at 550 °C from the total sample weight. Minerogenic matter includes carbonates and organic silica. However, silica at the study site comprises mainly silicate minerals of terrigenous origin while carbonates are negligible due to a lack of carbonate-bearing rocks at the catchment. A subsample of approximately 1 g was weighed for the grain size analysis. The samples were pretreated with 35% H_2O_2 heated up to 80 °C in order to remove organic matter. Each sample was sonicated for 5 min to prevent coagulation prior the grain size analysis with Coulter LS 200 Laser Diffraction Particle Size Analyser.

2.3.2. Pre-treatment of sediment samples for microplastic analysis

The second collector tube sample was used for microplastic analyses. The work was carried out in a clean lab under a laminar flow hood to protect samples from contamination. Sediment volume was measured after 24 h of settling in a measuring glass covered by a glass lid. Water from the trap samples was vacuum filtered through 12–15 μm paper filters (Munktell Ahlstrom, general purpose paper, size 90 mm, grade 1003) and the filters were stored on petri dishes.

The entire sediment sample was rinsed into 50 ml polypropylene (PP) centrifuge tubes with ultrapure water. Samples were centrifuged (VWR Mega Star 1.6) at 3000 rpm for 9 min with a brake rate of 6 for removing excess water. The float was filtered through a paper filter and the walls of the filtration funnel were rinsed with ultrapure water to prevent loss of particles as suggested by Hidalgo-Ruz et al. (2012). Filtrate, consisting of water and fine suspended material, was discarded.

Heavy-liquid density separation was performed on the material that remained on the bottom of a centrifuge tube. Heavy liquid separation is a common method for separating crushed rock or sedimentary material into different density fractions and it has been used for a wide range of applications such as separating microfossils or cryptotephra from sediments. We used heavy liquid solution (Lithium heteropolytungstate, LST Fast float) for extracting microplastics from clastic sediments. The LST fast float is a non-toxic, low-viscosity, thermally stable and recyclable solution proven to be an efficient alternative in heavy liquid separation (Mounteney, 2011). It has a maximum density of 2.85 g/ml and in this study it was diluted to a density of 2.0 g/ml with ultrapure water.

The centrifuge tubes with the sediment samples were filled with 20 ml of LST and mixed well. Samples were centrifuged using previously described settings and the supernatant consisting of microplastics and biogenic matter (density less than 2.0 g/ml) was decanted on a filter (Munktell Ahlstrom, general purpose paper, size 90 mm, grade 1003, pore size 12–15 μm) as described before. The material remaining on the bottom of the first tube (density >2.0 g/ml) was treated with LST three times in total.

The method was verified using two types of artificial microplastics, red PET fragments (density 1.3–1.4 g/ml, particle size 250–500 μm) and white HDPE fragments (density <1 g/ml, particle size 250 μm). Hundred pieces of both plastic types were added to a blank sample consisting of lake sediment that had been dated to be ca. 2000 years old. Particle recovery was tested with three replicate runs using the described LST protocol with new samples each time. The recovered particles were identified and counted under binocular microscope (Nikon SMZ-80, magnification of 6.3×). On average, 98% of the PET particles and 89% HDPE particles were recovered, which is in agreement with the recoveries described earlier for different methods (Imhof et al., 2012; Quinn et al., 2016). These values suggest a high efficiency of the LST heavy liquid separation protocol for sediment samples of small volume. Repeated density separations per each sample are necessary for extracting all plastic material from minerogenic material (Hidalgo-Ruz et al., 2012) and three separations were observed to remove artificial plastics efficiently from the sediment fraction. None of the missing particles were detected in the residual after three separations.

2.3.3. Contamination

Control samples were prepared and analyzed to assess laboratory contamination. Three samples were taken from a lake sediment core (Lake Korttajärvi) at 1.8 m sediment depth representing time of about 2000 years before present (Tiljander et al., 2003). The sediment samples were prepared as described above and the collected fragments and fibers were analyzed using FTIR. No synthetic polymers were identified from the control samples and hence our results can be considered reliable.

2.3.4. Identification of particles

The samples on the filters were free of inorganic material, but contained natural organic matter that was not further digested because of its minor concentration. Microplastics were visually selected from the filters under a binocular light microscope and transferred with micro tweezers into 15 ml centrifuge tubes filled with pre-filtered ethanol for storage and transportation. Later the contents of the centrifuge tubes were vacuum filtered to silver membrane filters (Sterlitech Co) with pore size of 5.0 μm and diameter of 25 mm. Tubes and filtration funnel were rinsed with pre-filtered (0.2 μm) ethanol to collect all of the particles. Next, filters were placed on closed glass petri dishes and dried at room temperature. Dry filters were taped to glass microscope slides.

Microplastics were identified and quantified with imaging FTIR (Agilent Cary 670 spectrometer and Cary 620 microscope equipped with 128 × 128 focal plane array (FPA) detector). FTIR spectra were measured in reflection mode, with a 15× cassegrain objective, spectral resolution of 8 cm^{-1}, 4 scans and a spectral range of 3800–800 cm^{-1}.25% of the total filter area was scanned. The

detection limit of FTIR is 20 μm, but the practice of hand-picking particles under a microscope sets the practical minimum particle size at ca. 100 μm. Spectral map data was analyzed with siMPle software (Primpke et al., 2020), which calculates correlations between sample and reference spectra and provides numbers, mass estimations and grain sizes of particles. Reference database contains open source and in-house measured spectra of common plastics including polyamide (PA), polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), acrylonitrile butadiene styrene (ABS), polyurethane (PU), polyvinyl chloride (PVC), and PMMA.

3. Results

3.1. Sediment accumulation

The dry weight of the accumulated sediment of growing season (GS) and winter season (WS) are 5.4 and 9.5 g, respectively and calculated sediment accumulation rates (SAR) are 12.71 g m^{-2} day^{-1} for the GS sample and 14.49 g m^{-2} day^{-1} for the WS sample (Table 1). Winter season includes the minerogenic influx of spring flood event, too. In contrast, sediment volume of the GS sample was larger than the volume of WS sample. This contradiction is a function of higher content of low density organic matter in GS sample (26%) compared to WS sample (10%). According to Udden Wentforth classification, both samples are defined as clays. However, the high organic content defines GS sample as gyttja.

3.2. Microplastic accumulation

The total measured number of plastic pieces; fragments and fibers is 24, of which 10 accumulated during the winter, and 14 during the growing season. Because only 25% of sample area was scanned, the total number of pieces was normalized up to 100%, thus leading to annual microplastic rate of 89 pcs m^{-2} day^{-1} (Table 2). The GS sample resulted in more than twice as high microplastic flux rates (131 pcs m^{-2} day^{-1}) as the WS sample (61 pcs m^{-2} day^{-1}). Microplastic concentration (pcs kg^{-1}) was also higher in GS sample (10 300 pcs kg^{-1}) compared to WS sample (4200 pcs kg^{-1}). The microplastics identified in the samples are PE, PP, and PET, while other polymer types were not detected. Plastic fragments dominate in the GS sample with PE being the most common plastic type, WS sample is dominated by fibers in general and particularly by those of PE.

The particle size (largest dimension) of the identified microplastic pieces varies in GS sample from 13 to 380 μm (mean 132 μm, median 95 μm) and in WS sample from 37 to 300 μm (mean 100 μm, median 83 μm) (Table 3).

Sediment trap monitoring reveals that the microplastic flux rate is higher during growing season than during winter time (Fig. 2). Comparison of SAR and microplastic flux rate (Fig. 2) shows that microplastic flux is indeed not related to sediment flux rate. The sediment accumulation rate is highest during the spring (WS sample) but the microplastic flux rate is lower than on summer (GS sample).

Plastic fragments dominate in the GS sample with PE being the most common plastic type, while WS sample is dominated by fibers in general and particularly by those of PE (Table 3, Fig. 3).

Table 1
Sediment trap intervals and measured sediment characteristics.

	GS sample	WS sample	Annual total
Trap down	Jun 3, 2017	Oct 23, 2017	Jun 3, 2017
Trap up	Oct 23, 2017	May 27, 2018	May 27, 2018
number of days	142	216	358
sample volume (ml)	63.5	22	85.5
dry weight (g)	5.44	9.45	14.90
SAR (g/m2/d)	12.71	14.49	13.8
MM %	74	90	n/a
OM %	26	10	n/a
Grain size (median; μm)	3.52	3.24	n/a

4. Discussion

4.1. Sediment trap method

Assessing the microplastic fluxes per area per time unit is a prerequisite for measuring the current flux of microplastics in different environments, for determining how rapidly the flux rate is changing, and identifying factors that influence the microplastic flux rates. This can be achieved through mass calculations carried out from well-dated sediment records (Brandon et al., 2019; Turner et al., 2019), or by using sediment traps (Enders et al., 2019). Dating of sediment cores is expensive and not always feasible. Furthermore, the inherent error margins of the routinely used dating methods range from a year up to tens of years, causing inaccuracies in the evaluated flux rates.

Sediment traps have been used already for a long time to monitor and measure the components of the sediment and

Table 2
Number of microplastic pieces at the sediment trap samples normalized to 100%.

Particle type	PE fragments	PE fibers	PP fragments	PP fibers	PET fragments	total
Growing season						
number of pieces	20	8	12	0	16	56
flux (pcs/m2/d)	26.7	18.7	28.0	n/a	37.3	130.6
pcs/kg	3671	1468	2202	n/a	2937	10 278
pcs/l	315	126	189	n/a	252	882
Winter season						
number of pieces	8	12	8	4	8	40
flux (pcs/m2/d)	12.3	18.4	12.3	6.1	12.3	61.3
pcs/kg	846	1270	846	423	846	4232
pcs/l	364	545	364	182	364	1818
Annual						
number of pieces	28	20	20	4	24	96
flux (pcs/m2/d)	25.9	18.5	18.5	3.7	22.2	88.8
pcs/kg	1879	1342	1342	268	1611	6443
pcs/l	327	234	234	47	281	1122

Table 3
Particle dimensions of the identified microplastic pieces by polymer groups. A) from growing season sample, and B) winter season sample. The shape of the pieces are fibers (f) and fragments (p).

A) Microplastics from Growing season (GS) sample				
MP identifier	Polymer group	Major dimension [μm]	Minor dimension [μm]	Shape
MP_1	PE	45	25	p
MP_2	PE	66	28	p
MP_3	PE	72	39	p
MP_4	PE	76	51	p
MP_5	PE	114	55	p
MP_6	PE	135	42	f
MP_7	PE	164	41	f
MP_8	PP	13	9	p
MP_9	PP	28	23	p
MP_10	PP	74	15	p
MP_11	PET	122	17	f
MP_12	PET	235	22	f
MP_13	PET	320	23	f
MP_14	PET	380	31	f
B) Microplastics from Winter season (WS) sample				
MP_1	PE	37	4	f
MP_2	PE	37	18	p
MP_3	PE	46	4	f
MP_4	PE	57	6	f
MP_5	PE	93	37	p
MP_6	PP	76	5,5	p
MP_7	PP	89	56	p
MP_8	PP	122	83	f
MP_9	PET	148	20	f
MP_10	PET	300	21	f

accumulation rates. Since the late 70's great efforts have been made to establish the sediment trap protocol, to determine the most presentative trap design and to define the limitations of the method. Laboratory experiments (Bloesch and Burns, 1980; Hargrave and Burns, 1979) and field operations (Gardner, 1980) report that while funnels tend to under trap particles the cylinder model is the most reliable trap shape producing results that are repeatable with an error margin within 10%. Studies have also shown that while the diameter of the collector tube should be larger than 5 cm, the aspect ratio of tube height to tube radius should be > 5 (Bloesch and Burns, 1980; Hargrave and Burns, 1979) in order to prevent material escape from the collector tube due to turbulence. The larger aspect ratio is suggested for higher water flows, however, the sediment traps are not suitable for turbulent waters. Most accurate vertical fluxes are reported in flows up to 15 cm s^{-1} (Bloesch and Burns, 1980; Gardner, 1980).

Horizontal and vertical in-situ differences in settling flux within the water column of a basin must be considered in research design, when determining the placement and number of needed sediment traps. However, in spatially limited sedimentation basins geometry, such as the single basin Huruslahti bay, it is relatively easy to estimate the volume of sediment deposition using classical methods. In a single or isolated basin systems it is a common practice to select the deepest part of the basin for investigating the sediment as well as contaminant flux rates (Pompeani et al., 2013; Thevenon et al., 2011; Tylmann et al., 2011; van Drooge et al., 2011; Verta et al., 1989; Zeng et al., 2014). This approach has also been applied in recent microplastic studies (Brandon et al., 2019; Turner et al., 2019) as well as in this investigation. However, if detailed mass calculations representing different zones of the basin were desired, the microplastic influx at littoral zones should be evaluated for example by using extra traps.

4.2. Seasonal cycle in sedimentation

The site for the sediment trap feasibility study was chosen carefully based on two major criteria 1) potential hotspot for microplastic accumulation, and 2) location where resuspension and bioturbation is minimized. Huruslahti Bay is ideal for testing sediment trap method for monitoring microplastic influx owing to its small and relatively deep basin, where thermally stratified waters lead to oxygen deficiency of the hypolimnetic waters (Zolitschka et al., 2015). Oxygen deficiency restricts bioturbation and the rather flat deep area of Huruslahti Bay further decreases the probability of sediment resuspension. Large depth-to-area ratio decreases likelihood of sediment mixing by wind and wave activity (Zolitschka et al., 2015). Hence, the sampling location is not disturbed by turbulent waters, erosion or resuspension of sediments. Instead, it is characterized by calm conditions and continuous sedimentation, yet changing sediment accumulation rates controlled by the seasonal cycle. The sampling location may receive additional microplastics from resuspended littoral sediments as a part of natural sedimentation processes such as sediment reworking and focusing (Blais and Kalff, 1995).

In the boreal environment, the sediment sources during the growing season are i) autochthonous biological production controlled by nutrient availability and temperature and ii) allochthonous biogenic and minerogenic matter from the catchment controlled by the sediment availability, biogenic productivity and precipitation-driven transport (Saarni et al., 2015). During winter, the lakes and ground are frozen and precipitation occurs as snow. Sediment transport from the catchment ceases due to a lack of flowing water and sediment availability due to ground frost and snow cover. Sedimentation during the period of ground frost and ice cover has been measured to be negligible (Johansson et al., 2019; Ojala et al., 2013) and mainly very fine grained degraded organic matter is accumulated (Saarni et al., 2015). However, WS sample includes spring flood event resulting from the episodic melting of snow. Spring floods cause enhanced catchment erosion and efficient transport of clastic matter from the catchment to the lake basin (Johansson et al., 2019; Ojala et al., 2013). The sediment source of a WS sample can be related to a rather short spring flood event, with main constituents being minerogenic particles (Ojala et al., 2013). This is reflected in significantly higher SAR and

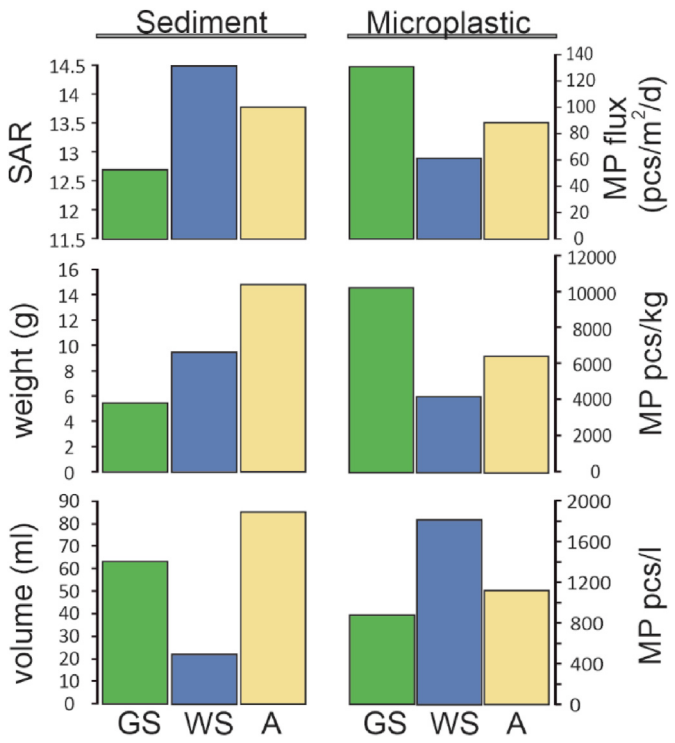

Fig. 2. Seasonal and annual sediment flux rates and microplastic flux rates, and microplastic concentrations with respect to sediment seasonal and annual sediment volume and dry weight. GS Growing season, WS winter season, A annual.

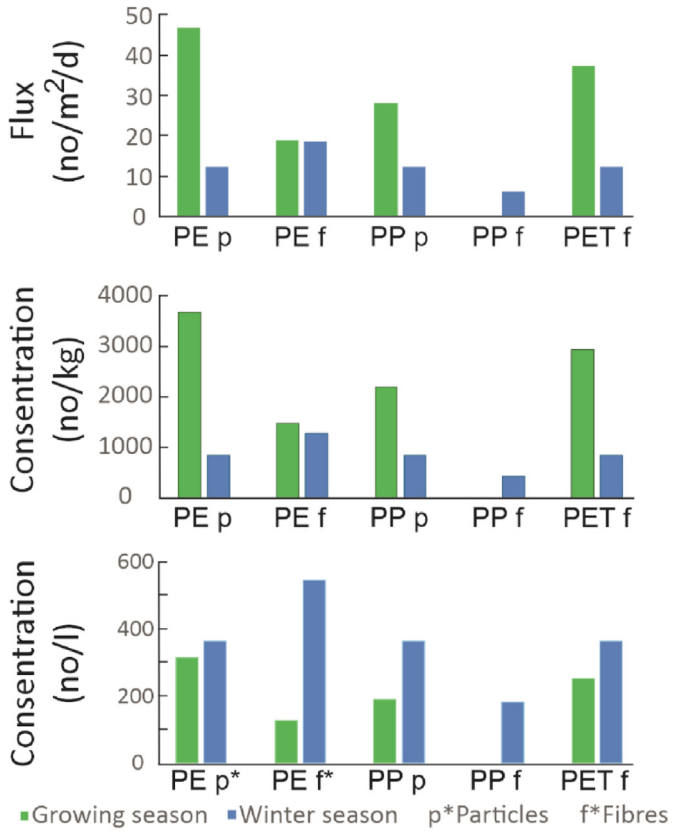

Fig. 3. Concentrations and calculated flux rates of different synthetic polymer types and particle classes.

minerogenic matter content (90%) in WS samples compared to GS samples (74%; Table 1).

4.3. Annual and seasonal microplastic flux rates

The annual flux rate of microplastics at the Huruslahti Bay, 32 400 pcs m^{-2} $year^{-1}$, is significantly higher than measured from a sediment trap at Arkona Basin, Baltic Sea (37 pcs m^{-2} $year^{-1}$; only microplastics > 500 μm; Enders et al., 2019) and from dated sediment cores at Santa Barbara Basin, off California, US (50 pcs m^{-2} $year^{-1}$; Brandon et al., 2019). It is also higher than the microplastic flux rate reconstructed from a sediment core from an urban Hampstead No 1. Pond, London (983 pcs m^{-2} $year^{-1}$; Turner et al., 2019). Brandon et al. (2019) and Turner et al. (2019) report comparable microplastic minimum limits as this study. This indicates that Huruslahti Bay is a microplastic contamination hot spot and also points at freshwater environments close to human activities being in a high risk for significant microplastic contamination.

The occurrence of the identified material types follow their production (Geyer et al., 2017). PE was the predominant microplastic material in both samples, most likely due to their extensive use, followed by PP and PET – all of them being used for packaging (Geyer et al., 2017). The microplastic flux is not related to sediment flux rates, instead, total microplastic flux rate is higher (lower) during summer (winter) while net sedimentation is lower (higher). This is in contradiction to sediment trap results reported from Arkona Basin (Baltic Sea; Enders et al., 2019) where enhanced microplastic flux is related to periods of higher sedimentation rate. However, the boreal lacustrine environment is markedly different from the Baltic Sea environment. The smaller microplastic amount in WS sample could partly be a result of trapping of microplastics from the water body into the lake ice during winter, and their consequent release at ice melt in the late spring. It has been shown that ice effectively concentrates microplastics within its structure during freezing (Geilfus et al., 2019; Peeken et al., 2018). Ice cover may also explain the relative increase of fibers compared to fragments in WS sample (Fig. 3.). Sheltered by the wave and wind activity, the settling of the fibers is favored under extremely calm waters (Bagaev et al., 2017; Khatmullina and Isachenko, 2017). Smaller particle size of microplastic pieces identified in WS sample compared to GS sample (Table 3) supports the assumption of the favorable conditions for particle settling under calm waters sheltered by the ice cover (Kathmullina and Isachenko, 2017). Open water conditions expose microplastics to more energetic environment as a result of wind and wave activity, deteriorating circumstances for fiber settling. This is in line with larger particle sizes identified in GS sample. Increased particle accumulation and frequent occurrence of PE and PP, with lower density than that of water, is likely related to biofouling. The development of biofilms and microplastic incorporation into organic aggregates can increase the density of the particle and diminish the hydrophobic nature, and hence facilitate sinking (Kaiser et al., 2017; Kowalski et al., 2016; Van Cauwenberghe et al., 2013; Van Melkebeke et al., 2020).

Seasonality can also influence on microplastic deposition rates also via controlling the availability of microplastics in the catchment. Frozen and snow-covered soil can retain microplastics as well as naturally occurring particles that are released and transported to water bodies during spring floods (Saarni et al., 2017). Unfrozen soil releases microplastics to the environment more efficiently, which can result in a higher microplastic influx on growing season, supplemented with particles released and transported through melting of snow, frost and ice cover. The reported residence times of PE, PP and PET particles in the water column prior to deposition or entering the beach sediments are estimated to be around 2 weeks at Baltic Sea at the time of calm waters and up

to 50 days during stormy or turbulent conditions (Schernewski et al., 2020) and hence most particles released during spring floods are likely deposited in the bottom sediments on following summer. At urban sites especially sewer overflow systems, including stormwater, as well as waste waters (treated and untreated) are major pathways for microplastics from catchment to water bodies (Liu et al., 2019; Schernewski et al., 2020) in addition to riverine input (Campanale et al., 2020; Schmidt et al., 2017; Siegfried et al., 2017). The overflow emissions but also discharge of land-based microplastics from the surroundings are related to heavy rain events (Campanale et al., 2020; Schernewski et al., 2020) of which likelihood at the study region is highest during summer months (June, July, August; FMI open data, 2020). This can also lead to increased microplastic entrance and hence enhanced accumulation in the aquatic environments during growing season.

The small grain size of the bulk sediment in both winter and growing season samples are very fine silt suggesting equally favorable settling conditions in terms of currents throughout the year. This highlights the importance of seasonal controls such as ice trapping and ground frost in reducing amount of available particles for accumulation as well as protecting from wind and wave activity and, on the other hand, importance of biofouling and increased precipitation in enhancing the accumulation and availability during growing season.

These results show that sediment trapping can be a powerful tool to monitor annual flux rates but also highlights the methods potential to facilitate our understanding on sedimentation processes of microplastics. Long term seasonal sediment trap monitoring can shed light on seasonal variability and controls of microplastic loads on a certain sedimentary environment. The traps enable identification of the hot spots and long term monitoring can provide valuable measures on trends in microplastic flux rates for modelling the future changes as well as for assessing the seasonal controls on microplastic accumulation in natural waters.

4.4. Concentrations compared to flux rates

Our results highlights the problems related to reporting microplastic concentrations from the sedimentary archives (Bancone et al., 2020). When reporting microplastic concentrations as pieces per liter (e.g. Woodall et al., 2014) or per kg of dry sediment, the results are quite different compared to flux rate. However, concentrations as pcs kg^{-1} reveal a similar pattern as the flux rates (Fig. 3). When comparing GS and WS samples with respect to volume, the outcome is very different and the concentration of microplastic is higher during WS suggesting major microplastic accumulation during the winter. The difference is an artefact resulting from comparison of heavier and denser minerogenic dominated WS sediment to organic-rich lighter but more voluminous GS sample sediment. This results in different volume per weight ratios that consequently influence the perceived microplastic concentrations. Furthermore, enhanced sedimentation rate causes dilution of microplastics. Such differences in sedimentation rate and composition are expected to occur spatially and temporally and, as shown, can vary even seasonally. Due to these variations the concentration of microplastics can vary regardless of the actual influx of microplastics. This could be of importance especially at sites with high sedimentation rates or large seasonal changes in sedimentation rates that could result in underestimation of the microplastic contamination rates if microplastic accumulation is expressed only with respect to sediment volume or dry weight. Very organic rich sediments can result overestimation (underestimation) of microplastics when reported with respect to sediment weight (volume) owing to their low density. This highlights the need for microplastic flux rate data with temporal constraints that facilitate between-site comparisons of variable environments and enable the identification of microplastic contamination hot spots. Flux rate is an accurate and precise way to express actual microplastic accumulation rate, because it is independent from changes in sedimentation rate or sediment composition, that significantly influence the sediment volume and weight (Bancone et al., 2020; Brandon et al., 2019; Turner et al., 2019). This should be acknowledged also when studying sediment cores, since biogenic matter tends to decay with time decreasing the bulk sediment volume down core. Additionally, compaction of sediment takes place as a result of sediment burial, and sediment volume may thus be an even more difficult measuring unit for microplastic concentrations than sediment dry weight.

This study shows that sediment trap monitoring can be a powerful tool to not only quantify local microplastic accumulation rates but also to further understand the behavior and processes controlling the fate of microplastic in aquatic environments. High microplastic fluxes enable short sediment trap deployment intervals, however, at sites with anticipated low microplastic input, longer trap deployment times and/or larger collector tube areas are potentially more suitable.

5. Conclusions

The microplastic burial rates into sediments are largely unknown, due to a tradition to investigate microplastic concentrations in sediments (pieces, pcs kg^{-1} dry weight or pcs l^{-1}). The rate of change in microplastic flux is in a key role for risk assessments and modelling purposes. We tested sediment trap, a classical tool for quantifying sedimentation rates and sediment compositions, as a method to monitor and measure microplastic flux rate into an urban freshwater lake with two sequential deployments of five and seven months. As a result, we can report microplastic concentration with respect to sediment dry weight and volume, as well as time. Annual microplastic flux rate at Huruslahti Bay is 32 400 pcs m^{-2} $year^{-1}$. Highest MP accumulation at our sampling site occurred during the growing season, while the highest sediment accumulation rate was measured during the winter season, as a result of intense catchment erosion during spring floods. This observation suggests that microplastic flux rate is not necessarily related to sediment flux rate but are controlled by seasonal conditions. These results reveal a great potential of sediment trap monitoring that can shed light on microplastic accumulation rates as well as identify microplastic sources and processes related to microplastic burial.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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