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Plastic pollution in Swiss surface waters: nature and concentrations, interaction with pollutants

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Environmental context. Plastic, and particularly microplastic, pollution is a growing environmental concern worldwide. Research regarding marine environments has led to a substantial increase in knowledge, yet little is known as regards the situation in freshwater environments. Although the occurrence of microplastics was demonstrated in Lake Geneva in 2012, the present research aims at confirming this pollution and expanding the data set for other lakes and environments of Switzerland.

Abstract. Marine microplastic (<5 mm) water pollution has met growing public and scientific interest in the last few years. The situation in freshwater environments remains largely unknown, although it appears that they play an important role as part of the origin of marine pollution. Apart from the physical impacts on biota, chemical effects are to be expected as well, especially with smaller particles. This study aims at assessing plastic abundance in Lakes Geneva, Constance, Neuchâtel, Maggiore, Zurich and Brienz, and identifying the nature of the particles, potential ingestion by birds and fishes, and the associated pollutants. Lake surface transects and a few rivers were sampled using a floating manta net, and beach sediments were analysed. Plastics were sorted by type (fragments, pellets, cosmetic beads, lines, fibres, films, foams) and composition (polypropylene, polyethylene, polystyrene, etc.); fish and water birds were dissected to assess their potential exposure, and analyses were conducted on the hydrophobic micropollutants adsorbed to the microplastics as well as some potentially toxic additives they contained. Evidence of this pollution is shown for all lakes, microplastics of all types and diverse composition having been found in all samples. Birds and fish are prone to microplastic ingestion, and all the tested chemicals (both adsorbed micropollutants and contained additives) were found above the detection limit, and often the quantification limit. The sources and their respective contribution need to be confirmed and quantified, and the ecotoxicological effects need further investigation. Other questions remain open, including the transport and fate of plastic particles in the environment.

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Introduction

Microplastics are generally defined as plastic particles smaller than 5 mm,[1] a size above which they become macroplastics.[2,3] The latter can degrade and fragment to become secondary microplastics,[3,4] but microplastics can also be engineered as such, in which case they are called primary microplastics,[5] for example to be used as feedstock for the plastic industry, or as industrial or cosmetic scrubbers.[6] Their effects can be visual, physical through entanglement or obstruction,[7] or potentially chemical through adsorption of hydrophobic contaminants and release after ingestion, or direct leaching of plastic additives.[5] The harmful properties of plastics due to their chemical characteristics have been widely discussed,[8] some studies concluding they pose significant risks (see for example Tanaka et al.,[9] Fossi et al.[10] and Oliveira et al.[11]) whereas others consider their role is minor in the uptake of chemicals by biota, and that they have few effects (see for example Koelmans et al.,[12] Gouin et al.,[13] Besseling et al.[14] and Koelmans et al.[15]). There is, however, general consensus pointing to the need to expand ecotoxicological research to draw stronger conclusions. Plastics occurrence and accumulation in marine environments have been documented since the 1970s,[2,4] yet very little data are available for freshwater systems.[16] The existing studies have shown the occurrence of microplastic pollution on the Great Lakes surface and beaches,[17–19] Lake Garda's beaches[20] and Lake Hovsgol in Mongolia.[21] Rivers are considered as major pathways for plastic pollution, as suggested in studies on the Danube,[22] the Thames,[23] the Seine[24] and the Los Angeles and San Gabriel rivers.[25] Just like marine organisms, freshwater biota also seem prone to microplastic ingestion,[20] and even larger organisms such as fish are affected.[26]

Exploratory results revealed the occurrence of plastic and microplastic pollution in Lake Geneva,[27] as well as plastic ingestion by water birds and adsorption of polychlorinated biphenyls (PCBs) on plastic particles from Lake Geneva,[28] although data were lacking to draw quantitative conclusions.

Table 1. Geographical and population data of the studied lakes[29]

Lake	Surface area (km^2)	Volume (km^3 $\times 10^6$)	Residence time (years)	Watershed area (km^2)	Population
Geneva	581.3	89 900	11.4	7393	850 000
Constance	539	48 530	4.3	10856	1 448 000
Neuchâtel	217.9	14 170	8.25	2670	260 000
Maggiore	212.3	37 100	4.12	6386	550 000
Zurich	68.15	3770	1.4	1740	330 000
Brienz	29.8	5170	2.69	1127	26 600

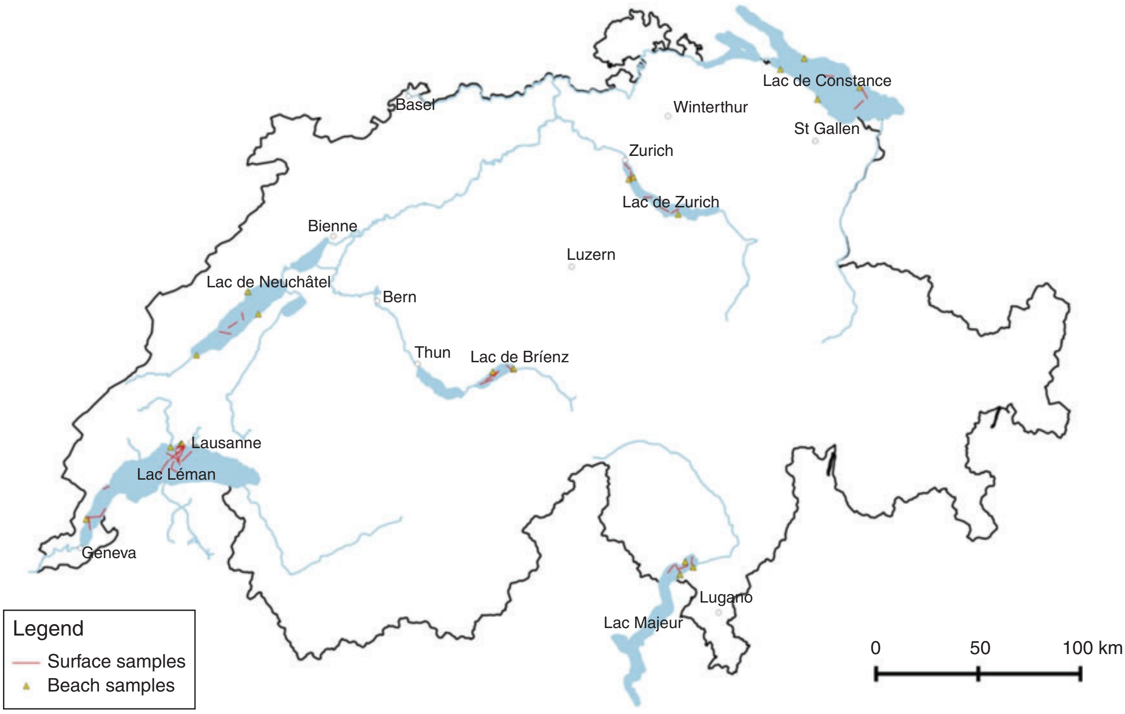

Fig. 1. Overview of sampling sites.

Based on the first findings and the concerns of the scientific community, the present study aimed at expanding the data set of microplastic pollution in Switzerland and better understanding its distribution, behaviour and impact. It aimed primarily at giving a first assessment of microplastic water pollution in Switzerland by sampling the surface and beaches of six of the largest Swiss lakes, identifying the abundance, type and composition of the plastic particles and getting a first glance of sources and the fate of these particles. Another aspect of the present study is related to fish and bird exposure to plastic as well as the identification and quantification of adsorbed pollutants and plastic additives.

The resulting data contribute to filling the most pressing knowledge gaps regarding microplastics in fresh water. Although no ecotoxicological assessment was made, the aim was rather to give a broad assessment of the extent and nature of this pollution.

Methods

Study area

Six of the largest Swiss lakes were chosen for surface and beach sediment sampling in order to cover various geographical regions, highly or less densely populated watersheds and shores (Table 1 and Fig. 1): Lake Geneva, Lake Constance, Lake Maggiore, Lake Neuchâtel, Lake Zurich and Lake Brienz. The latter was added as a presumably less-polluted lake in a less-densely populated Alpine region.[29] The Rhone River was sampled both upstream (Pont de l'Île) and downstream (Chancy Bridge, which is the Rhone's border point with France) from Geneva, as well as just upstream from Lake Geneva. Other inlets among Lake Geneva's most important ones were sampled as well: the Aubonne and Venoge as well as an urban stream, the Vuachère. Sampling took place between July and October 2013 for the lakes and after October 2013 for the rivers. At each stage and for all samples, precautionary measures were taken to avoid contamination: clothes made out of natural fibres, air exposure of samples as limited as possible, use of Milli-Q water, cleaning and observation of all tools and containers with a stereomicroscope before their use. Some plastic fragments found after observation that resembled the plastic of the containers were discarded, to avoid any contamination through abrasion of the containers.

Beaches

A target of three sampled beaches per lake was set, with three replicates being sampled on each beach. Sand and gravel beaches were preferred, representing various exposures to wind and currents, population density, proximity to inlets or outlets, etc. On each beach, 0.3 × 0.3-m quadrats were drawn on the drift line, the beach being divided into four equal parts, except for beaches longer than 100–m where the samples were collected every 15 m. A depth of 5 cm was set, resulting in a sample volume of 4.5 L, within the range of those in similar studies.[30] Overall, 67 samples were collected, of which 33 from 19 different beaches were analysed. Samples were stored in 5-L plastic (polypropylene, PP) buckets at 4 °C until analysis, and and a first reduction of the sample volume using gravity separation in salt-saturated water was carried out, this method being until now the most widely used.[4,30,31] More efficient techniques exist,[32] but require prohibitively costly instruments and consumables. Sand (250 mL) is poured into 7 L of saline solution (320 g NaCl L^{-1}), and stirred 3 × 2 min in a continuous air flow, with 3-min resting in between and the supernatant is collected through a 300-μm sieve and separated into fractions >5 mm (macroplastics), >1 mm (large microplastics) and >300 μm (small microplastics). Macroplastics and large microplastics are identified visually and sorted under a stereomicroscope. The smaller fraction is dried 24 h at 60 °C, and undergoes wet peroxide oxidation as adapted from Baker et al.[33] to eliminate part of the organic matter: 35 % H_2O_2 with 0.05 M Fe^{II} catalyst for 6 h, these values of concentrations and exposure time being too low to affect plastic particles.[31] All plastic fractions are then sorted into eight categories, counted and weighted. Results are extrapolated to particle number and mass per square metre (particles m^{-2}, mg m^{-2}), because these are the most common units in the literature,[20,30,34] in order to be more easily comparable. These can also easily be converted into abundance and mass per cubic metre (particles m^{-3}, mg m^{-3}), knowing the sampling depth was always 5 cm, with a factor of 20.

Surface and rivers

A floating manta trawl, the most commonly used device for such samplings,[30,35] was used for surface sampling, with a 300-μm mesh and 60 × 18-cm opening. The trawl was maintained 3 m along the windward side of the boat to avoid wake waves, generally towed along 3 to 4 km to filter 320 to 430 m^3 of surface water (mean 360 m^3) at a speed of ~1.5 m s^{-1} (3 kn) and in low-wind conditions when possible to avoid excessive vertical mixing of the particles[36] and ensure a steady flow through the net opening. The boat path was recorded by global positioning system (GPS), and the flow measured with a mechanical flow meter attached at the trawl opening. Three to five trawls were carried out for all lakes, in order to represent different zones (Fig. 1): the middle of the lake, proximity to inlets or urban centres. Areas of potential accumulation were avoided (bays because of temporary gyres and the near-coast owing to currents parallel to the shore). A total of 23 trawls were carried out on Lake Geneva in different zones, sand and meteorological conditions. Altogether, 39 samples were analysed. The samples were stored at 4 °C in 180-mL plastic (polystyrene, PS) tubes in salt-saturated water until analysis. Fourteen samples were collected for chemical analysis following a specific procedure and using special material under conditions to gather the largest plastic quantities. The same analysis protocol was followed as for beach sediment samples without the sedimentation process. In addition, organic matter smaller than 300 μm, mainly containing plankton, was weighed, in order to compare the proportions of plankton and small microplastic.[37] Results were extrapolated to particles and mass per square kilometre (particles km^{-2}, mg km^{-2}) knowing what surface was covered by the trawl, because these are the most common units used in the literature[30] and in order to be more easily comparable. A similar sampling procedure was applied for the rivers, the trawl being attached on a bridge downstream from a straight portion of the river for 15 to 30 min, the flow meter measuring the flow being filtered. Here, the results are given in particle count and mass per filtered cubic metre and per hour (particles m^{-3}, mg m^{-3}, particles h^{-1}, mg h^{-1}).

Fauna – fish and birds

Forty fish from Lake Geneva were dissected and their gut contents rinsed, sieved and observed through a stereomicroscope: 10 bleaks (*Alburnus alburnus*), 10 European perch (*Perca fluviatilis*), 10 common roach (*Rutilus rutilus*) and 10 common dace (*Leuciscus leuciscus*). The fish were caught in two campaigns in 2010 and 2012 within the Swiss Federal Institute of Aquatic Science and Technology's (Eawag) assessment of the Swiss fish fauna ('Projet Lac'),[38] and were selected among the collection in order to cover the largest possible range of sizes (from juvenile to maximal adult size for each species). They were fished using the standards of the European Committee for Standardization's multi-mesh gillnets and vertical benthic and pelagic nets in order to represent various zones of Lake Geneva (near shore and central areas, near and far from urban centres, etc.), and with different mesh sizes. The whole fishes were then stored in 75 % alcohol at the Naturhistorisches Museum der Burgergemeinde Bern until analysis. A third of the digestive tracts could not be entirely analysed, having being damaged during storage or analysis: the thinnest parts of the intestine were somewhat clogged and dried out. They were analysed as far as possible, but may lead to a slight underestimate of the final values if some plastic particles were missed. Nine birds were similarly investigated: one grey heron (*Ardea cinerea*), three mute swans (*Cygnus olor*) and five mallards (*Anas platyrhynchos*). Two swans were juveniles, all other birds were adults. All birds were found dead on the NW shore of Lake Geneva between Lausanne and Nyon by conservation officers and brought to the Galli-Valerio Veterinary Institute, where their guts were removed and frozen until analysis. Apart from one swan, all birds were found thin, with the beginning of autolysis of the corpses.

Plastic identification, pollutants analysis

Plastics were identified visually under the stereomicroscope, extracted from the organic matter and, for each size class, were sorted in categories according to their appearance, characteristics and possible origin. Potential contamination through abrasion of the containers had been tackled by the removal of all particles of similar colour. If doubt existed about the plastic nature of a particle, it was discarded. These two procedures probably led to an underestimation of the final concentrations, but cannot be quantified. Eight categories were detailed after the ones that can be found in the literature[22,39,40]: fragments of larger plastic objects, preproduction pellets, microbeads from cosmetics, lines such as fishing lines, textile fibres, thin films, foams and others. The category 'others' was not taken into account in the final count. Of all plastics that could have come from cosmetics, only spherical microbeads were identified as such, particles presenting other shapes[6,41] being classified as fragments. For each category and size class, particles were counted and weighed to the nearest 0.1 mg. In total, 375 particles from 14 surface samples and 6 beach samples (all 169

Table 2. Measured micro- and macroplastics densities in beach sediments of Swiss lakes

Lake	*n*		Microplastics (particles m^{-2})	Microplastics (mg m^{-2})	Macroplastics (particles m^{-2})	Macroplastics (mg m^{-2})
All lakes	33	Mean ± s.d.	1300 ± 2000	920 ± 1500	90 ± 250	14 000 ± 33 000
		Median	270	110	11	480
		Min.–max.	20–7200	1–6000	0–1300	0–150 000
Geneva	6	Mean ± s.d.	2100 ± 2000	960 ± 1100	35 ± 65	18 000 ± 40 000
		Median	1700	6000	0–170	0–100 000
		Min.–max.	78–5000	19–2900		
Constance	4	Mean ± s.d.	320 ± 220	240 ± 340	8 ± 11	1300–2300
		Median	260	99	6	170
		Min.–max.	140–620	23–750	0–22	0–4800
Neuchâtel	4	Mean ± s.d.	700 ± 1100	920 ± 1700	17 ± 26	6400 ± 13 000
		Median	220	110	6	49
		Min.–max.	67–2300	1–3500	0–56	0–25 000
Maggiore	9	Mean ± s.d.	1100 ± 2300	450 ± 870	28 ± 42	26 000 ± 54 000
		Median	180	76	11	780
		Min.–max.	20–6900	3–2600	0–120	0–150 000
Zurich	4	Mean ± s.d.	460 ± 350	380 ± 670	3 ± 6	690 ± 1400
		Median	480	69	0	0
		Min.–max.	89–800	16–1400	0–11	0–2800
Brienz	6	Mean ± s.d.	2500 ± 3000	2400 ± 2700	400 ± 510	16 000 ± 12 000
		Median	1200	1800	190	18 000
		Min.–max.	89–7200	14–6000	11–1300	480–28 000

macroplastics, and 206 large microplastics making up 10 % of these samples, randomly chosen) were analysed through Fourier-transform infrared attenuated total reflectance (FT-IR ATR) spectroscopy to identify their composition.

The same 14 samples from the surface of Lake Geneva, Lake Maggiore, Lake Constance and Lake Brienz together with 6 beach samples from Lake Geneva and Lake Brienz were used for chemical analysis. As sufficient quantities for analysis were needed (*a priori* estimated as 100 mg plastic per analysis), the samples were collected after rain events (input of higher concentrations of floating material), on longer distances or close to coasts (e.g. in bays or near inflows). For these, non-plastic tools were used for sampling to avoid any contamination, cleaned with acetone and hexane (as well as dichloromethane, DCM, at analysis), stored at 4 °C in glass tubes with Teflon lids and then at −20 °C after sorting. In total, 14 samples were recombined into 25 subsamples of a minimum of 100 mg per subsample (preliminary estimation of the limit of detection) to allow comparisons based on the sampling site and water–sediment matrix, particle size, polymers, particle categories or the influence of prior rainfall. Four groups of compounds adsorbed onto the particles were investigated: 12 PCB congeners, 16 polycyclic aromatic hydrocarbons (PAHs), 19 organochloride pesticides (OCPs) and 14 polybrominated diphenyl ethers (PBDEs), as well as three groups of additives: phthalates, nonylphenols (NPs) and bisphenol A (BPA) (experimental procedure adapted from Hirai et al.[42]). PCBs, PAHs, OCPs and phthalates were analysed using gas chromatography–tandem mass spectrometry (GC-MS/MS), and NPs and BPA using liquid chromatography–tandem mass spectrometry (LC-MS/MS). The following blanks were used:

- Three equipment blanks, 500-mg low-density polyethylene (LDPE) bands cleaned with DCM and methanol
- Three method blanks, with extraction into an empty tube
- Four instrument blanks of 10 mL DCM reduced to 1 mL, after the instruments were rinsed with acetone, hexane and DCM.

Limits of detection (LOD) and quantification (LOQ) were calculated as $\mathrm{LOD} = \bar{x} + 3\sigma$ and $\mathrm{LOQ} = \bar{x} + 10\sigma$.[43] Values under the LOD were declared non detected (n.d.), those between LOD and LOQ were noted separately because they lead to semiquantitative results.

Results and discussion

Beaches

Microplastics were found in all 33 beach sediment samples, and macroplastics in 21 of them. Figures for each lake are given within a range, because maximum and minimum densities were consistently found on different beaches (Table 2). Substantial plastic densities were found locally, even when few particles were found in samples from other beaches of the same lake. This confirms the findings from similar studies on Lakes Erié[18] and Garda,[20] because ~90 % of plastic particles were found on a single beach. Replicates within the same beach show much less variability, as can be observed for lakes Maggiore and Brienz (Table 3). In both cases, beaches near major inflows are by far the most plastic-rich: the River Maggia for Lake Maggiore (beach of the Parco della pace), and Aar for Lake Brienz (Aaregg). This was also the case for the Lake Garda study,[20] most of the plastic particles being found near the Sarca River inflow, although the authors favour the action of wind as the main explanation for the greater density.

Surface

The 39 surface samples did contain microplastics, and 7 did not contain macroplastics. Concentration variability is significant among as well as within the lakes, the measured concentrations indicating the order of magnitude rather than absolute numbers (Table 4). The number of small microplastics (<1 mm) found was 5.6 times that of large microplastics, the average particle of the latter being 8.2 times heavier. Smaller particles having a greater specific surface area, their adsorption and leaching potential is increased.

Table 3. Details of plastic densities in beach sediments of lakes Maggiore and Brienz

Lake, beach	n		Microplastics (particles m^{-2})	Microplastics (mg m^{-2})	Macroplastics (particles m^{-2})	Macroplastics (mg m^{-2})
Maggiore, Parco della pacce	3	Mean ± s.d.	3000 ± 3400	1300 ± 1200	74 ± 45	77 000 ± 75 000
		Median	1600	990	67	77 000
Maggiore, Vira	3	Mean ± s.d.	78 ± 87	30 ± 40	4 ± 6	780 ± 1300
		Median	33	11	0	0
Maggiore, Gerra	3	Mean ± s.d.	130 ± 51	56 ± 42	7 ± 13	260 ± 450
		Median	100	54	0	0
Brienz, Aaregg	3	Mean ± s.d.	4800 ± 2600	4700 ± 1200	770 ± 480	22 000 ± 5300
		Median	5100	4500	690	19 000
Brienz, Oberried	3	Mean ± s.d.	200 ± 100	32 ± 24	26 ± 17	9900 ± 15 000
		Median	230	22	11	2200

Table 4. Measured micro- and macroplastics densities at the surface of Swiss lakes

Geneva (Grand Lac) values are those for Lake Geneva excluding all samples taken after rain events and in coastal zones. Geneva (Petit Lac) values only include transects entirely in the Petit Lac

Lake	n		Microplastics Mean	Microplastics Median	Microplastics s.d.	Macroplastics Mean	Macroplastics Median	Macroplastics s.d.
All Swiss lakes	27	(particles km^{-2})	91 000	48 000	120 000	1800	860	3100
		(mg km^{-2})	26 000	8500	33 000	44 000	12 000	80 000
Geneva (Grand Lac)	4	(particles km^{-2})	220 000	220 000	160 000	2300	2400	1700
		(mg km^{-2})	46 000	57 000	25 000	44 000	50 000	33 000
Geneva (Petit Lac)	4	(particles km^{-2})	33 000	14 000	46 000	1100	835	710
		(mg km^{-2})	10 000	9400	11 000	27 000	25 000	23 000
Constance	3	(particles km^{-2})	61 000	63 000	12 000	830	390	1100
		(mg km^{-2})	45 000	54 000	31 000	16 000	3200	25 000
Neuchâtel	3	(particles km^{-2})	61 000	62 000	24 000	290	0	500
		(mg km^{-2})	7600	7000	3000	1900	0	3300
Maggiore	4	(particles km^{-2})	220 000	220 000	150 000	6500	5300	6300
		(mg km^{-2})	69 000	77 000	48 000	170 000	140 000	160 000
Zurich	5	(particles km^{-2})	11 000	9800	2600	580	0	980
		(mg km^{-2})	3700	2800	4200	13 000	0	28 000
Brienz	4	(particles km^{-2})	36 000	30 000	23 000	950	1200	630
		(mg km^{-2})	4500	4100	3400	28 000	26 000	27 000

Higher concentrations such as that measured on Lake Maggiore could be explained by the rainfall event preceding sampling for this lake, as was observed in marine coastal waters near river inflows.[37] On Lake Geneva, in the same zones and under similar wind conditions, microplastics were 4.4 times more abundant in number and seven times heavier after large rain events, and 9 and 9.5 times respectively for macroplastics. Wind preceding sampling on Lakes Zurich and Constance may on the contrary have lowered the amount of measured particles owing to vertical mixing.[36] Conversely, a strong 'bise' (NE wind) creating a temporary gyre[44] at the edge of the Petit and Grand Lac (Golfe de Coudrée) may account for higher plastic densities, up to 410 000 particles km^{-2} and 94 000 mg km^{-2} for microplastics. This sample was not taken into account for the Petit Lac average.

The particle concentrations are of similar magnitude to most marine plastic pollution data. Freshwater references are scarce for the time being; densities found on the Laurentian Great Lakes are overall slightly lower[17]: an average of 43 000 particles km^{-2} for three lakes with a 333-µm mesh, rising to 110 000 particles km^{-2} for Lake Erié with a maximum at over 466 000 particles km^{-2}. Densities found on Lakes Zurich or Brienz are rather in the range of that of Lake Hovsgol, Mongolia, a large remote mountain lake where an average of over 20 000 particles km^{-2} were measured over nine transects.[21] In general, direct riverine inputs and a smaller surface less prone to vertical mixing may lead to higher measured concentrations on the lakes of limited size investigated.

Rivers

Mostly fragments and foams were found on the rivers. Pellets once more represent only a small fraction in number, but a larger fraction in mass (up to 52 % of the particle mass found in the Venoge, and 33 % in the Rhone downstream from Geneva), and can be expected to be more represented deeper in the water column because of their higher mass per particle and their ability to remain suspended. The concentrations were higher after rain events (Table 5), and this is particularly true for rivers in urbanised areas. The Vuachère, mainly fed by street runoff water during rain events, shows an abundance 150 times higher in the single sample that was taken in such conditions (41 000 particles h^{-1}, 4900 mg h^{-1}, 680 particles m^{-3}, 81 mg m^{-3}). Densities are five times higher for the Venoge after a rain event (three times in mass), its higher flow buffering rain runoff. The concentrations are also much higher downstream from Geneva than upstream, especially in terms of mass. However, these figures need to be taken carefully, because the samples were not collected on the same day. There are not enough data to establish mass balances of plastic in Lake Geneva, but the data available do give insights for future studies, namely focus on runoff and sewer overflows, which may be plastic carriers under rainy conditions. Although other studies dealing with riverine plastic pollution have mainly focussed on macroplastics so far,[23,24] a study of the Danube[22] has some similarities with the present methods, although the nets used were dipped somewhat deeper (0.5 m) and had a slightly wider mesh (0.50 mm). Particle concentration is higher in the case of the Swiss rivers because of the mesh size. The mass is, however, much lower, possibly because of the respective proportion of the water column being filtered. An extrapolation to the entire water column with a mean flow of 343–m s^{-1}[45] and assuming a homogeneous distribution of plastic densities through the water column has been calculated. The flow of plastic out of Switzerland through the Rhone River can be estimated at less than ~14 kg day^{-1}, or 570 kg day^{-1} into the Mediterranean assuming inputs proportional to the population.[46] These numbers can be put into perspective by comparison with 4.2 Mg day^{-1} estimated for the Danube.[22]

Fauna

The weight ratio of small particles of organic matter (<1 mm, mainly composed of plankton) to small microplastics is 25.8 ± 27.8 (mean ± s.d.) for 21 samples. This suggests a lower availability of plastic to planktivorous organisms, unlike what was found in some marine studies,[47,48] although in the present study, the plankton was not specifically identified and separated and the methods are somewhat different. In only one station did the mass of plastic exceed that of plankton, and it was of the same order of magnitude for four other samples.

Plastic fragments and fibres were found in three fish out of the 40 that were analysed: two common dace (*Leuciscus leuciscus*) with two and one fragments of mass 0.3 and 0.1 mg respectively, and one bleak (*Alburnus alburnus*) with 31 fibres weighing 0.2 mg overall. Of the fish analysed, the 7.5 % that contained plastics can be compared with the 12 % of wild gudgeons (*Gobio gobio*) from French rivers that were found contaminated by plastics.[26] Microplastic ingestion by fish in Lake Geneva is demonstrated, but more samples, including from other lakes, should be investigated to obtain more representative results, including other fish species such as gudgeons (*Gobio gobio*) or vendace (*Coregonus albula*).

Bird pellets had previously shown the temporary ingestion of plastic by birds on the shores of Lake Geneva.[27] Eight of the nine dissected birds now showed plastic particles in their digestive tract, with a mean of 4.3 ± 2.6 particles and 4.8 ± 8.9 mg per bird, and a maximum of nine particles and 26 mg. Most of these particles were fragments, but foams, films, microbeads and fibres were found. The fact that most of the particles were found in the gizzard together with their polished aspect suggest a fairly long exposure time of the birds to the adsorbed pollutants and chemicals they contain. It would be

Table 5. Measured microplastic density in Swiss rivers

River	*n*		Microplastics Mean	Microplastics Median	Microplastics s.d.	Macroplastics Mean	Macroplastics Median	Macroplastics s.d.
All rivers	24	(particles h^{-1})	790	141	1600	1.9	0.0	3.5
		(mg h^{-1})	170	42	284	83	0.0	210
		(particles m^{-3})	7.0	0.36	0.20	0.012	0.0	0.034
		(mg m^{-3})	1.4	0.20	3.4	0.43	0.0	1.2
Rhône, upstream	4	(particles h^{-1})	1200	1100	380	2.4	2.0	2.8
		(mg h^{-1})	140	100	110	230	20	430
		(particles m^{-3})	2.3	2.4	0.53	4.5×10^{-3}	3.9×10^{-3}	5.3×10^{-3}
		(mg m^{-3})	0.26	0.20	0.17	0.43	0.039	0.81
Aubonne	4	(particles h^{-1})	48	4.	26	0	0	0
		(mg h^{-1})	9.0	10	5.4	0	0	0
		(particles m^{-3})	0.10	0.10	0.042	0	0	0
		(mg m^{-3})	0.020	0.023	0.013	0	0	0
Venoge, dry	3	(particles h^{-1})	670	360	630	3.8	0	6.7
		(mg h^{-1})	180	14	290	150	0	260
		(particles m^{-3})	6.5	4.0	5.3	0.034	0	0.060
		(mg m^{-3})	1.6	0.16	2.6	1.3	0	2.3
Venoge, rainy	2	(particles h^{-1})	5400	–	3100	5.5	–	7.7
		(mg h^{-1})	1000	–	41	170	–	240
		(particles m^{-3})	64	–	35	0.067	–	0.095
		(mg m^{-3})	12	–	0.92	2.1	–	2.9
Vuachère	2	(number h^{-1})	89	–	50	0	0	0
		(mg h^{-1})	14.5	–	13	0	0	0
		(particles m^{-3})	4.4	–	1.3	0	0	0
		(mg m^{-3})	0.67	–	0.46	0	0	0
Rhône, Geneva	4	(particles h^{-1})	57	49	40	0	0	0
		(mg h^{-1})	3.6	3.9	0.85	0	0	0
		(particles m^{-3})	0.13	0.12	0.076	0	0	0
		(mg m^{-3})	$8.4 \cdot 10^{-3}$	$8.6 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$	0	0	0
Rhône, Chancy	5	(particles h^{-1})	160	150	30	2.5	2.0	2.8
		(mg h^{-1})	190	190	51	58	9.5	100
		(particles m^{-3})	0.29	0.25	0.08	4.7×10^{-3}	3.5×10^{-3}	5.3×10^{-3}
		(mg m^{-3})	0.35	0.32	0.11	0.11	0.017	0.19

interesting to investigate healthy individuals, all of the birds except the one with no plastic having been found emaciated and with a 'low amount of normal-looking content in the digestive tract' according to the autopsy reports.

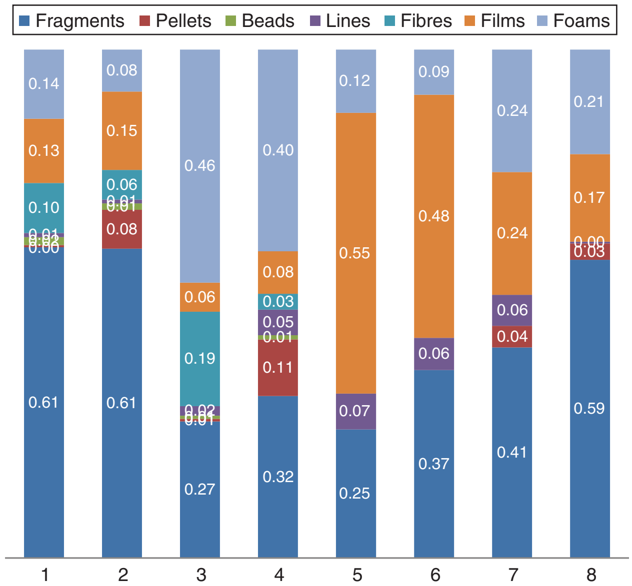

Fig. 2. Proportion of plastic categories by count and mass: (1–2): surface micro (n = 29 000, m = 9.4 g); (3–4) beach micro (n = 4 400, m = 3.0 g); (5–6) surface macro (n = 430, m = 27 g); (7–8) beach macro (n = 270, m = 42 g).

Plastic identification and pollutants

Proportions for each plastic category are detailed in Fig. 2. The main difference between count and mass proportions comes from pellets, with a significant mass despite a low count, and in contrast foams and fibres, which are on average lighter per particle. Foams were found in greater proportions on the beaches, maybe because of a higher buoyancy. As for the composition of the 375 particles analysed through FT-IR ATR spectroscopy, 62 % was PE (mainly films, used for packing[49]), 15 % PP (mostly in fragments) and 12 % PS (mainly foams from the beaches). Films were mainly PE, the main polymer used for packaging in Switzerland,[49] whereas fragments were rather made out of PP. Foams were mainly expanded PS, which are used mainly in buildings as insulating material or the food industry. Of the only beach sample analysed here, 4 % of the particles were PVC, which is considered to be too dense to be retained with the methods used for sedimentation; it is one of the five most toxic polymers because of its additives.[50] Only 2 % of the tested particles were not plastic, suggesting careful visual sorting is reliable.

All tested pollutants, adsorbed hydrophobic contaminants or those contained as plastic additives, were measured above both LOD and LOQ, in concentrations that can be compared with those found in marine studies (Table 6). In general, beach microplastics are less contaminated than surface particles, but results vary greatly with sampling station, type and size of particle and the analysed compound (Fig. 3). Particles from Lake Brienz were always less contaminated than those from other lakes, possibly because of a less human-influenced and

Table 6. General results of the chemical analysis, and marine reference data[42,55–57] (ng g^{-1})

Polychlorinated biphenyls (PCBs): Σ7: CB28 (PCB congener 28), CB52, CB101, CB138, CB153, CB180, CB118; organochloride pesticides (OCPs): dichlorodiphenyltrichloroethane (DDTs), dichlorodiphenyldichloroethylene (DDEs), dichlorodiphenyldichloroethane (DDDs), Mirex, hexachlorobenzene (HCB); polycyclic aromatic hydrocarbons (PAHs): Σ14: benzo(*a*)anthracene, benzo(*a*)pyrene, benzo(*b*)fluoranthene, benzo(*e*)pyrene, benzo(*g*,*h*,*i*)perylene, benzo(*k*)fluoranthene, chrysene, dibenzo(*a*,*h*)anthracene, fluoranthene, fluorene, indeno(1,2,3-*c*,*d*)pyrene, phenanthrene, pyrene, acenaphthene; polybrominated diphenyl ethers (PBDEs): Σ13: 17, 28, 47, 66, 71, 85, 99, 100, 138, 153, 154, 183, 190; bisphenol A (BPA): nonylphenol; phthalates: Σ7: dibutyl phtalate (DBP), bis(2-ethylhexyl) phthalate (DEHP), di-isobutyl phthalate (DiBP), Di-*n*-octyl phthalate (DNoP), di-isononyl phthalate (DiNP), benzyl butyl phthalate (BBP), diethyl phthalate (DEP). Limit of detection (LOD); limit of quantification (LOQ)

	Mean	Median	Interval	LOD	LOQ	North Pacific gyre	San Diego beach	Mediterranean
PCBs	97.6	32.5	0.4–548.2	0.2–1.4	0.4–2.3	0–2856	2.5–47	
OCPs	187.3	37.5	1.4–2715	0–0.7	0–2.0	0.02–2700	0.56–75	
PAHs	1202	523	86–5714	0–13.0	0–27.9	1–14500	18–1900	
PBDEs	125.9	107.2	0.2–419.1	0–35.8	0–96			
BPA	16.6	–	4.8–28.3	0	0	0–800		
Nonylphenol	199.3	92	0–612.2	0	0	0–4000		
Phthalates	18039	8924	528–111604	0–1721	0–3346			5–172

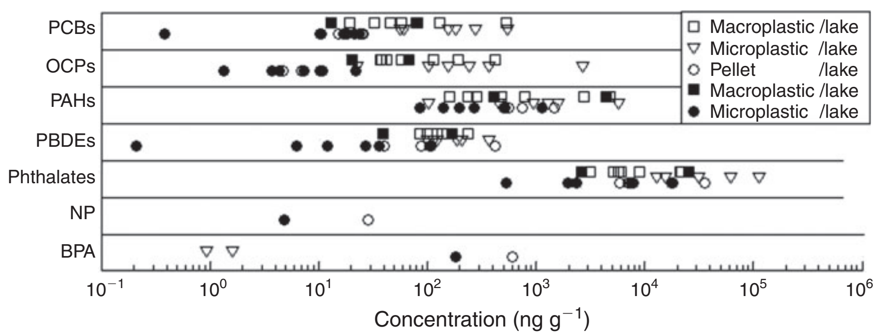

Fig. 3. Overview of contaminant concentrations per particle type and substrate; see Table 6 for details of the analysed compounds and definitions.

industrialised watershed, with mainly atmospheric sources. Some of the most concentrated samples (mainly for PCBs and OCPs, especially DDT) were found on Lake Maggiore, on the quite closed bay in front of Locarno. Residence time may be longer because of the isolation of the Locarno Basin, with a confined and stagnating water mass[51] enhancing adsorption, but higher water contaminant levels can also explain these concentrations. Overall, particles sampled after large rain events contain lower concentrations of adsorbed compounds, but higher ones of additives. This can be due to a shorter residence time not allowing additives to leach through long diffusive paths or contaminant adsorption to reach equilibrium, or to the easy release of the external POPs adsorbed to the outer parts of the particles. The same phenomena can be observed with beach samples, with lower concentrations of additives and that experienced strong leaching. The tested compounds are three to six times more concentrated on microplastics than on macroplastics, probably because of a higher age as they partly come from fragmented bigger particles, or alternatively because of a greater specific surface area and surface area-to-volume ratio . This is less obvious with phthalates, which should rather be more prone to leaching from smaller particles.[52] PE seems to have more affinity for pesticides and PAH, and less with phthalates. The similar phenomena generally observed with PCBs[53,54] could not be witnessed here.

Outlook

Plastic was found in all investigated matrices (beach sediments, lake and river surfaces), confirming its ubiquity and diversity. Densities in mass are generally lower than in similar marine studies, yet the densities in number of particles are often larger. Flow into rivers is probably a major pathway for plastics although wind transport cannot be excluded. Ingestion of plastic particles by fauna is now demonstrated. The physical effects of plastic ingestion were not demonstrated, but these particles could provide a way for hydrophobic pollutants and plastic additives into the trophic chain although it might not be the main input pathway for these compounds: this topic is subject to ongoing research, and no final conclusions can be drawn. These pollutants were found in rather high concentrations, especially regarding adsorbed compounds, which suggests a rather long exposure time for equilibrium to be reached. Smaller particles, which represent most of the particles found, have the largest specific surface area, and are thus more prone to compound adsorption or leakage. More data are needed in order to better understand the variability in densities and nature of this pollution. Other substrates and environments, such as benthic sediments in lakes and rivers, will have to be studied. Some of the potential pathways for microplastics in the Swiss environment, such as wastewater treatment plants or urban runoff, are currently being investigated. More research should also be undertaken on the effects of this pollution, so as to expand our knowledge of biota exposure to plastic particles and their associated pollutants.

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