Riverine litter in a small urban river in Marseille, France: Plastic load and management challenges

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Riverine Litter in a small Urban River in Marseille, France: Plastic Load and Management Challenges

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Abstract

Small urban rivers are thought to be major sources of riverine litter, especially macroplastics, into the ocean. In well-developed countries, waste management infrastructures and recovery systems are sometimes implemented to prevent their emission into the sea meeting environmental and economic goals. The Huveaune River in Marseille, South of France, is a typical case study showing a non-negligible and uncontrolled leakage of riverine litter remains, despite all recovery systems implemented. Giant bar screens are settled over the river to collect riverine litter from the whole water column before water is released into the Sea. In this paper, screened material was characterized during a dry, wet and heavy rainfall period and annual macroplastic mass flows were estimated. The plastic fraction represented 83% by count of the 3147 items sorted and counted. Mass flow of plastic debris ranged between 1.1–5.7 mt/yr (equivalent to 2.1–11.1 g/cap/yr), in which 0.4–2.0 mt/yr (equivalent to 0.8–3.9 g/cap/yr) are bypassed to the sea during heavy rainfall periods. Giant bar screens across the Huveaune River

prevent 65% of the mass flow to reach the sea annually, but 35% remain uncontrolled. When compared to the Seine River and other European Rivers, plastic leakage into the ocean per capita may range between 1 and 10 g/cap/yr, despite well-developed recovery systems are implemented. This suggests that end-of-pipe solutions are not enough and further supports urgent regulations of the plastic production on local to global scales to tackle the plastic pollution at its source. Those regulations may consider economico-social innovations focused on changes in consumption habits and use.

1. Introduction

"Marine plastic litter entering the ocean is increasing, the impacts of plastic pollution on marine and coastal ecosystems are worsening, and our increasing understanding of the negative impacts of plastic pollution on human health is creating greater urgency to act." This is how the last UN report commissioned by the G20 (UN Environment Programme, 2021) introduces the problem, sounding the alarm on the uncontrolled leakage of plastics into the ocean which is thought to triple by 2040 (Lau et al., 2020). On a global scale, plastic emissions into the Ocean reach 0.8 – 2.7 million metric tons per year (mt/yr) according to the most recent model of riverine plastic export (Meijer et al., 2021). Those authors refined global annual emissions of plastics (excluding microplastics) based on Mismanaged Plastic Waste (MPW) generation calibrated with and validated by field studies using visual counting across the world (mostly Europe and Asia). In contrast to previous models suggesting few rivers were responsible for 80% of the global plastic emissions (e.g. Lebreton et al., 2017; Schmidt et al., 2017), Meijer et al. (2021) concluded that this proportion rather corresponds to more than 1,000 rivers most of which are small urban rivers in South East Asia. At the European scale, another modeling approach based on a wide database of riverine floating macrolitter (>2.5 cm) also recognized the relative importance of small basins (<100 km^2) close to coastlines (González-Fernández et al., 2021). Their model highlighted well-developed countries as non-negligible sources of riverine litter despite an improved waste management and well-developed recovery systems. These considerations highlight the need of critical case studies in river basins where those recovery systems are used.

Plastic transport along rivers are chaotic with storage and remobilization episodes or flushing episodes depending on river geomorphology, riparian vegetation and hydrological regime (Ivar do Sul et al., 2014; Liro et al., 2020; Tramoy et al., 2020a, 2020b; Honorato-Zimmer et al., 2021). Small urban rivers close to coastlines may then actually appear to be major plastic sources for the ocean. But, estimates of plastic loads remain challenging, especially during extreme meteorological events. Stormwater discharged in those rivers during rainfall episodes are probably major sources of riverine litter (Weideman et al., 2020; Treilles et al., 2021). Thus, meteorological events like heavy rainfall episodes must be better considered by monitoring protocols, which is not always the case with visual counting leading to conservative estimations (Castro-Jiménez et al., 2019; González-Fernández et al., 2021). That is why indirect quantification methods using environmental management data are interesting (e.g. Tramoy et al., 2021).

In this study, another indirect approach was applied in the Huveaune River in Marseille (870,000 inhabitants, Southern France), based on existing grey infrastructures collecting riverine litter over the whole water column. According to the International Institute for Sustainable Development, "grey infrastructures involve engineered assets that provide one or multiple services required by society, such as transportation or wastewater treatment". In this case, the grey infrastructure prevents riverine litter to reach the Mediterranean Sea close to the highly frequented Prado beach. Nowadays, water is redirected to the south of Marseille (i.e., Cortiou) after being bar screened. Bar screens are passive technical devices, which capture riverine litter as described for other type of passive devices by van Emmerik and Schwarz

(2020). When water flow is too high (> 30 m^3/s), water overflows the dam to prevent damages of infrastructures and is bypassed to the Prado beach without any treatment. The Huveaune River is a small urban river of 50 km length (~2 m^3/s) and is known for its relative high contamination in PCBs, a persistent organic pollutant, related to industrial and urban areas (Kanzari et al., 2014), but also a constant visual pollution of macrolitter.

In this case study, we explore how grey infrastructures collecting riverine litter together with opportunistic grab sampling in the screened materials can help to characterize riverine litter composition and orders of magnitude of macroplastic mass flows. Riverine litter were characterized by litter type and item categories according to the OSPAR/TSG-ML classification (MSFD Technical Subgroup on Marine Litter, 2013) for a dry, wet and heavy rainfall period. Only mass flows of macroplastics were estimated using mass/number ratios from literature. Then, macroplastic emission into the sea was estimated based on the volume of water overflowed toward the Prado beach (i.e., into the Sea) and its plastic mass concentration. Finally, macroplastic mass flows were normalized to the basin population to enable reliable comparisons through spatial scales between The Huveaune River, the Seine River, and other European rivers.

2. Material and method

2.1. The Huveaune watershed

The Huveaune watershed is located southern France (**Figure 1A**) and is 597 km^2 wide with more than 664,000 inhabitants (**Figure 1B**; https://www.syndicat-huveaune.fr/le-bassin-versant-de-lhuveaune/caracteristiques-du-bassin-versant-de-lhuveaune/). Water management in the Huveaune River, including bar screening, is performed by the company "Service d'Assainissement Marseille Métropole" (SERAMM for Sewerage Service Marseille Metropolis). The grey infrastructure asset consists in a dam with concrete dykes and a basic water pre-treatment plant with bar screens and sand traps (**Figure 1C**). The whole water column is passing through the infrastructure. The aim is to better manage the flood risk of the downstream part of the river, but also to prevent beaching of riverine litter on the Prado Beach or other pollutants to reach the Sea without treatment. Instead, treated water is redirected to the Sea through underground pipes. Screened material is automatically collected, dumped and managed by SERAMM for appropriate treatment. Water flow is monitored at a high frequency (every hour), as well as overflows toward the Prado beach for reporting to the authorities. In this study, Pugette is considered as the most downstream point of the Huveaune River. Based on GIS analysis, 512,000 inhabitants are living in the Pugette Basin (**see "Pop. PugetteB" in sup. Data**).

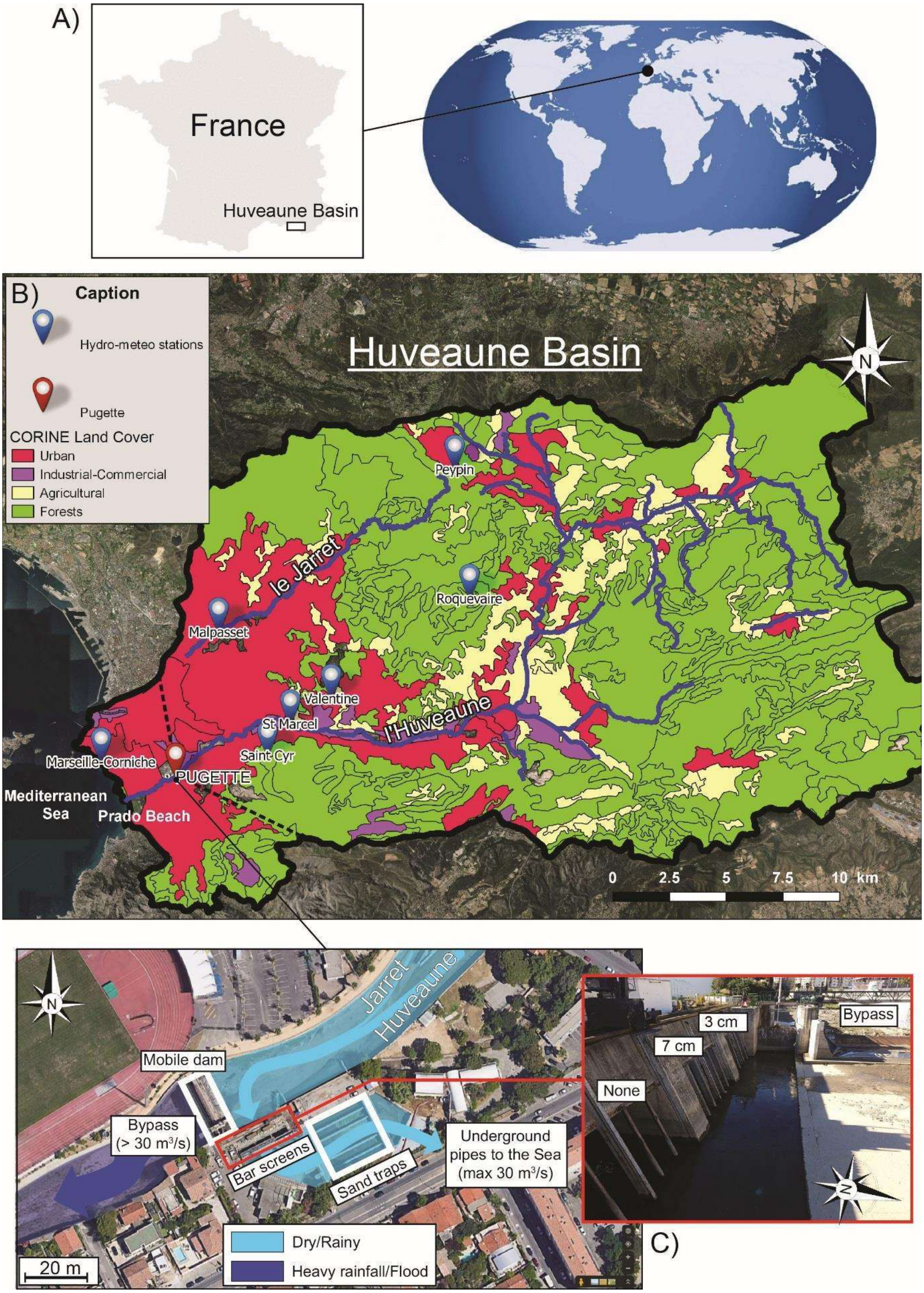

Figure 1: Map of the study site Pugette. A) The Huveaune Watershed is located Southern France. B). The Huveaune watershed is mainly covered by forests, but urban, industrial and commercial areas are concentrated

along its main course, with Marseille megacity downstream. Land cover is based on CORINE Land Cover-CLC12 (https://www.statistiques.developpement-durable.gouv.fr/corine-land-cover-0?rubrique=348&dossier=1759). The water treatment plant of Pugette is located 2 km upstream the Prado beach which constitutes the outlet of the Huveaune River. Pugette defines the basin limits for plastic mass flow calculation per capita (dashed lines). See 2.2 for details on the hydro-meteorological stations and their respective use. C) The water treatment plant in Pugette is equipped with vertical bar screens of 3 cm and 7 cm spacing to prevent coarse anthropogenic debris to reach the Mediterranean Sea. A bypass prevents damages and overflow on the structure during heavy rainfall episodes (≥ 30 m^3/s). Water is bar screened during dry and regular wet periods (<10 m^3/s).

The dam lying on the main channel in Pugette acts as a bypass for water flow above 30 m^3/s to prevent damages to the structure during heavy rainfall episodes and consecutive flash flood events (**Figure 1C**). The fraction of bypassed water directly flows into the sea, west of Marseille, bringing all pollutants on the Prado beach and into the sea (**Figure 1B**). The Jarret River is a tributary of the Huveaune River, which is partly underground until it flows into the Huveaune River few meters before Pugette station. Screening of coarse material is performed by passive technical devices at Pugette station using aligned automatic bar screens with spacing of 3 cm and 7 cm (**Figure 1C**). All the material collected is routinely sent to landfills. The 3 cm bar screens always work. The 7 cm bar screens work with water flow above 5 m^3/s. Between 10 m^3/s and 30 m^3/s, water can escape through underground pipes toward the sea, south of Marseille, without any screening. In fact, the excess water above 10 m^3/s reaches the sea without screening either to the south through pipes or to the Prado beach for the overflowed fraction above 30 m^3/s.

Similar grey infrastructures do exist in another small waterway called Les Aygalades, north of Marseille, but the riverine litter collected has been investigated for only one wet period, while water flow is not currently monitored and population on the watershed not well constrained. For those reasons, this sample has been ruled out. However, SERAMM reports the mixed quantity of riverine litter collected by both infrastructures. It reaches 585 ± 138 mt/yr over the period 2012-2019.

2.2.Hydrology

Over 2017 and 2018, the mean water flow in The Huveaune River is 2.4 ± 2.7 m^3/s at Pugette with a median value of 1.8 m^3/s (min = 0.1 m^3/s and max = 70.2 m^3/s), which corresponds to the sum of water flows recorded at Malpasset (the Jarret River) and at St Marcel (The Huveaune River; **Figure 1B**). The year 2017 was particularly dry, while 2018 was particularly wet (**Figure 2**). In order to determine the average time of dry, wet and heavy rainfall periods over a mean year at the basin scale, we compiled the occurrence and magnitude of daily precipitation recorded on the watershed at Marseille Corniche, Roquevaire and Peypin stations in 2017 and 2018 (https://www.infoclimat.fr/climato/; **Figure 1B**). Based on the precipitation alert thresholds in Pugette station (SERAMM, pers. Com), the daily precipitations characterizing wet and heavy rainfall periods was set as follows: Dry < 2 mm $\leq$ wet > 30 mm $\leq$ heavy rainfall periods. Hence, on average, the dry periods correspond to 87.5% of the time, the wet periods to 11.1%, and the heavy rainfall periods to 1.5% over 2017 and 2018 (**See “Precipitation” in sup data**). Volumes of water overflowed toward the Prado beach are available for 2018 and 2019 with 6.2 10^6 m^3/yr on average over the period (**See “Water flow” in sup data**).

In total, three samples were analyzed during dry, wet and heavy rainfall periods determined close to Pugette station according to the occurrence and magnitude of maximum precipitation recorded at Valentine, St Cyr and Pugette stations (**Figure 1B**). Precipitation patterns in this small watershed quickly results in changes in water flow at the study site (**Figure 2**). The period designated as “dry period” in Pugette corresponded to 21 days of litter accumulation in dumpsters without significant precipitation during summer between the 20^{th}

July and the 9th August 2017 with a mean water flow at Pugette of 0.9 ± 0.3 m^3/s. During this period, all the water volume was bar screened at 3 cm.

The designated "wet period" corresponded to 7 days during autumn between the 1st November and the 7th of November 2017 with a single rainfall event occurring the 5th of November. Cumulated precipitation was 49.2 mm with a peak water flow of 14.8 m^3/s and a mean water flow of 1.3 ± 2.5 m^3/s over the whole period. During the surveyed "rainfall event", the water flow was on average of 14.0 m^3/s for at least 3 hours, meaning 43,200 m^3 were not bar screened at all and 54,000 m^3 were bar screened at 7 cm, which is respectively 28.5% and 35.7% of the total volume at that time. The remaining 35.8% were thus bar screened at 3 cm.

The designated "heavy rainfall period" corresponded to 3 days during summer between the 7th of August and the 9th of August 2018, but the surveyed "heavy rainfall event" occurred the 9th of August. Cumulated precipitation was 76.6 mm with a mean water flow of 4.5 ± 7.9 m^3/s and a short duration peak to 34.4 m^3/s (~1h) over the whole period. During the heavy rainfall event, the water flow was on average of 23.0 m^3/s for at least 9 hours, meaning 421,200 m^3 were not bar screened at all — in which 15,840 m^3 overflowed to the Prado beach — and 162,000 m^3 were bar screened at 7 cm, which is respectively 56.5% and 21.7% of the total volume at that time. The remaining 21.8% were thus bar screened at 3 cm. So, less than the half of the water volume has been bar screened.

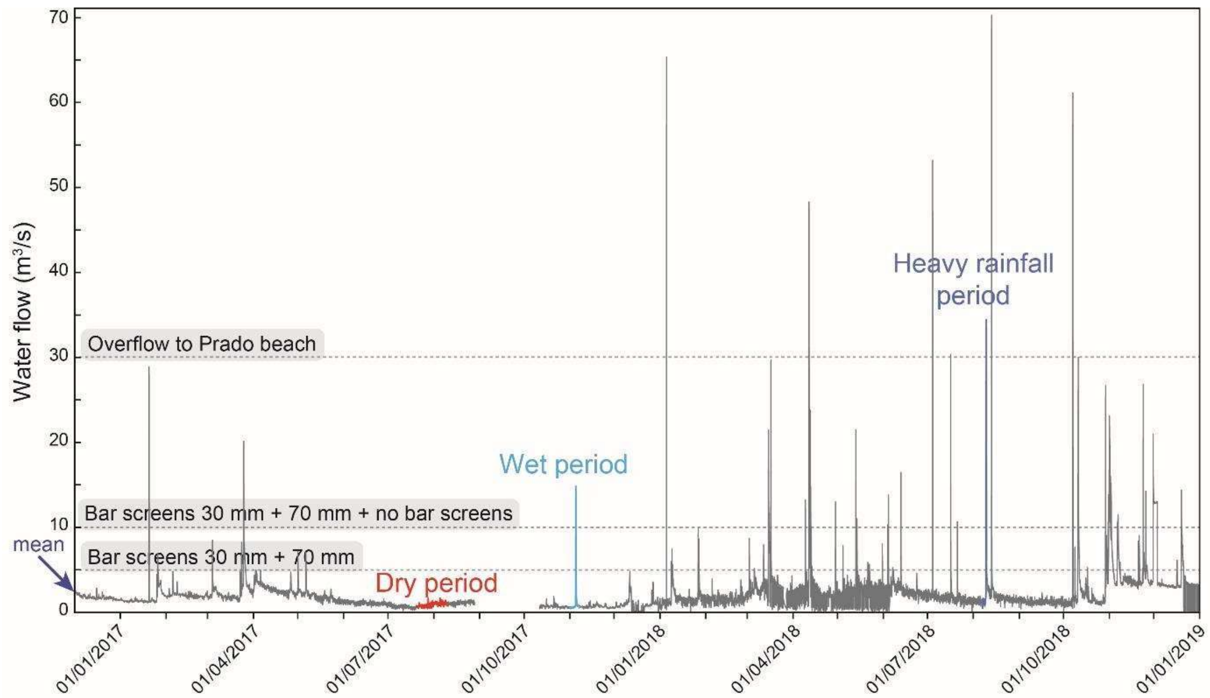

Figure 2: Water flow in the Huveaune River at Pugette. Periods of sampling are reported in red (dry), clear blue (wet) and dark blue (heavy rainfall). Thresholds of bar screens functioning suggest that bar screens work most of the time over the year. Null values during summer 2017 correspond to missing data related to technical issues.

2.3. Sampling procedure

Grab sampling were performed in Pugette station where organic and anthropogenic debris are automatically screened and transferred into dumpsters, which are big waste containers in metal with a volume ranging from 19 to 28 m^3 (**Table 1**). For the purpose of this ad-hoc study, dumpsters were emptied when they were completely full for sampling, whereas their content are usually sent to landfills. So the volume of waste in dumpsters was equal to the volume capacity of dumpsters. Sampling was performed once by SERAMM and the NGO MerTerre after each dry, wet, and heavy rainfall period to quantify organic *versus* anthropogenic litter in volume and to determine the composition of anthropogenic litter by count. Each sample corresponds to one full dumpster, filled by material coming from both 3 cm and 7 cm bar screens. Complete filling of dumpsters took 21, 7 and 3 days for dry, wet and heavy rainfall periods, respectively. The sampling procedure is described and illustrated in **Figure 3**.

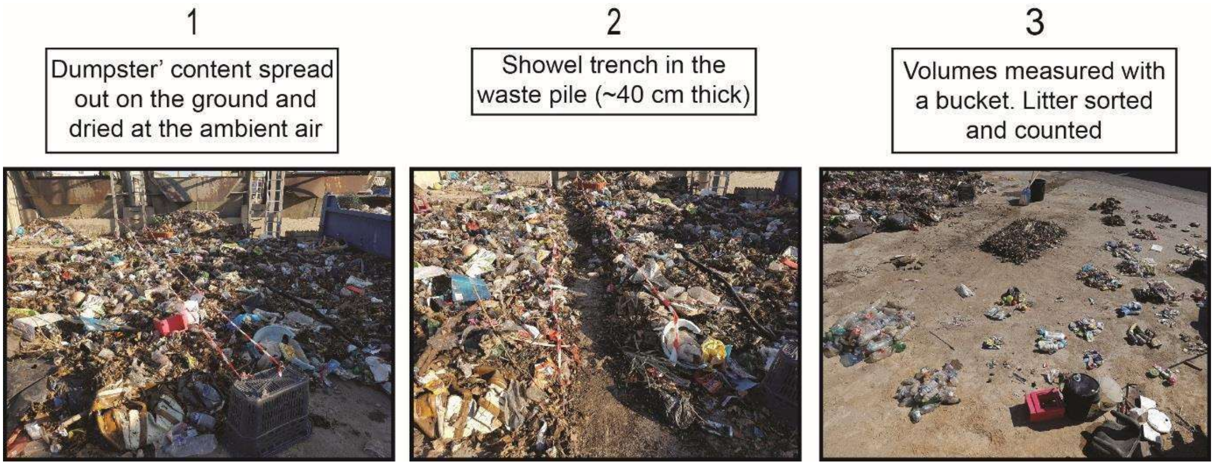

Figure 3: Sampling procedure.

In summary, dumpster' content was spread out on the site ground and air-dried for 9 to 14 days. Considering the huge volume of waste, waste that would be blown away or blown in by wind are negligible and no waste flights were noticed. Samples were randomly taken from the pile of waste by making a trench with a shovel. In each sample, organic debris and anthropogenic waste were separated and their respective volume were measured by filling by hands (without tapping down) a series of buckets with a known volume capacity (e.g. 10 full buckets of 100 l give 1000 l of material collected). Between 356 and 1,000 l of litter were sampled, equivalent to 1.3–4.2% of the total volume of litter that were in dumpsters (**Table 1**). The anthropogenic debris were sorted and counted according to their type of material and item categories following the OSPAR/TSG-ML classification (MSFD Technical Subgroup on Marine Litter, 2013). Unfortunately, those debris were not dried and clean enough (sediments and organic material were stuck on waste) to get reliable masses of each waste category. Thus, only count by item category was reported giving a number of item per unit of volume that can be extrapolated to the total volume of dumpsters.

Table 1. Sampling strategy of the screened materials in The Huveaune River (Pugette station). *The accumulation time corresponds to the time needed to fill the dumpsters full of riverine litter.

	Pugette (dry)	Pugette (wet)	Pugette (heavy rainfall)
Period of accumulation	20/07/2017 09/08/2017	01/11/2017 07/11/2017	07/08/2018 09/08/2018
Accumulation time* (days)	21	7	3
Sampling date	18/08/2017	16/11/2017	23/08/2018
Waste in Dumpter (l)	19,000	24,000	28,000
Sample size (l)	600	1,000	356
Sampled ratio (%)	3.2	4.2	1.3
Rate of filling (l/days)	905	3,429	9,333

2.4. Waste quantities and mass flow of plastics

For each of the three samples, the number of litter items was extrapolated to the volume of the corresponding dumpster and hydrological period to get a number of items accumulated per day for each dry, wet and heavy rainfall period (**see "Litter load" in sup. Data**). Except during rainfall episodes, most of water is bar screened. Thus, the litter items accumulated in dumpsters roughly corresponds to the litter items transiting in the river. However, an unknown fraction of litter is not bar screened for wet periods with a water flow above 10 m^3/s, leading to underestimations. It is then assumed that the concentration of litter in water that is not bar screened is equal to the concentration of litter in water (items/m^3) that is bar screened at the same time.

Only mass flow of macroplastics was calculated, because number to mass ratios are more reported for macroplastics in literature dealing with riverine litter than for other type of waste (van Emmerik et al., 2018; Schöneich-Argent et al., 2020; Vriend et al., 2020). The mass flows of macroplastics M_P (kg/d) for each hydrological period p_i were calculated using equation 1, with the estimated number of plastic debris N accumulated per day extrapolated to t time and converted to mass by a mass/number ratio m_p. Plastic debris include item categories from G1 to G124 according to the OSPAR/TSG-ML classifications. The number of plastic debris was converted into mass using a realistic number to mass ratio based on the mass distribution of thousands of macroplastics found in 3 German rivers, i.e median value of 1.0 g/macroplastic as the min value and 5.3 g/macroplastic on average as the max value (Schöneich-Argent et al., 2020, 2021). This interval seems reasonable, because the mean mass per plastic debris was 3.2 g in the highly polluted Saïgon River in Vietnam Van Emmerik et al., 2018), whereas this mass was 5.4 g in the far less polluted Rhine River (Vriend et al., 2020).

$$M_P(p_i) = N(p_i) \times t(p_i) \times m_p \text{ (equation 1)}$$

The $M_P(x)$ was extrapolated to a year and weighed relative to the mean fraction of time corresponding to dry, wet and heavy rainfall periods to get a mean annual mass flow of plastic debris. Then, macroplastic emission into the sea was estimated based on the volume of water overflowed toward the Prado beach (monitored by SERAMM), i.e., into the Sea and its plastic mass concentration, and its mass concentration in macroplastic (**See "Water flow" in sup data**). This estimate is conservative, because litter potentially passing through bar screens or not screened (for $10 < \text{water flow} \leq 30\ m^3/s$) and finally reaching the sea is not quantifiable by nature. Thus, corresponding mass flows of macroplastics were only reported to the water volume, which has been bar screened (**See "Water flow" in sup data**). Finally, macroplastic mass flows were normalized to the basin population to enable reliable comparisons through spatial scales.

3. Results and discussion

3.1. Composition of the screened materials

Organic debris versus anthropogenic debris

Bar screens settled on the full width of the Huveaune River captured large volume of debris, i.e. 0.9 to 9.3 m^3/d (**Table 1**). Organic debris in screened materials are a major fraction in volume relative to the total volume of debris (**Figure 4**). The highest fraction of organic debris is recorded during wet periods corresponding to 73% of the total volume. In contrast, the dry period recorded in The Huveaune River shows the highest fraction of anthropogenic materials, i.e. 61%. The heavy rainfall event recorded in The Huveaune River shows intermediate level of anthropogenic waste (55%) and organic debris (45%). The fraction of organic debris is greater during the wet period than during the dry and heavy rainfall periods most probably because the two latter were sampled during summer, whereas the wet period correspond to the autumn season where trees are losing their leaves. Treilles et al. (2021) also reported more organic material during autumn than during the rest of the year in screened material of runoff water in a peri-urban area. In any case, organic debris may enhance transport of plastic debris as demonstrated in Vietnam where plastic transport correlated with concentrations of water hyacinths (van Emmerik et al., 2019).

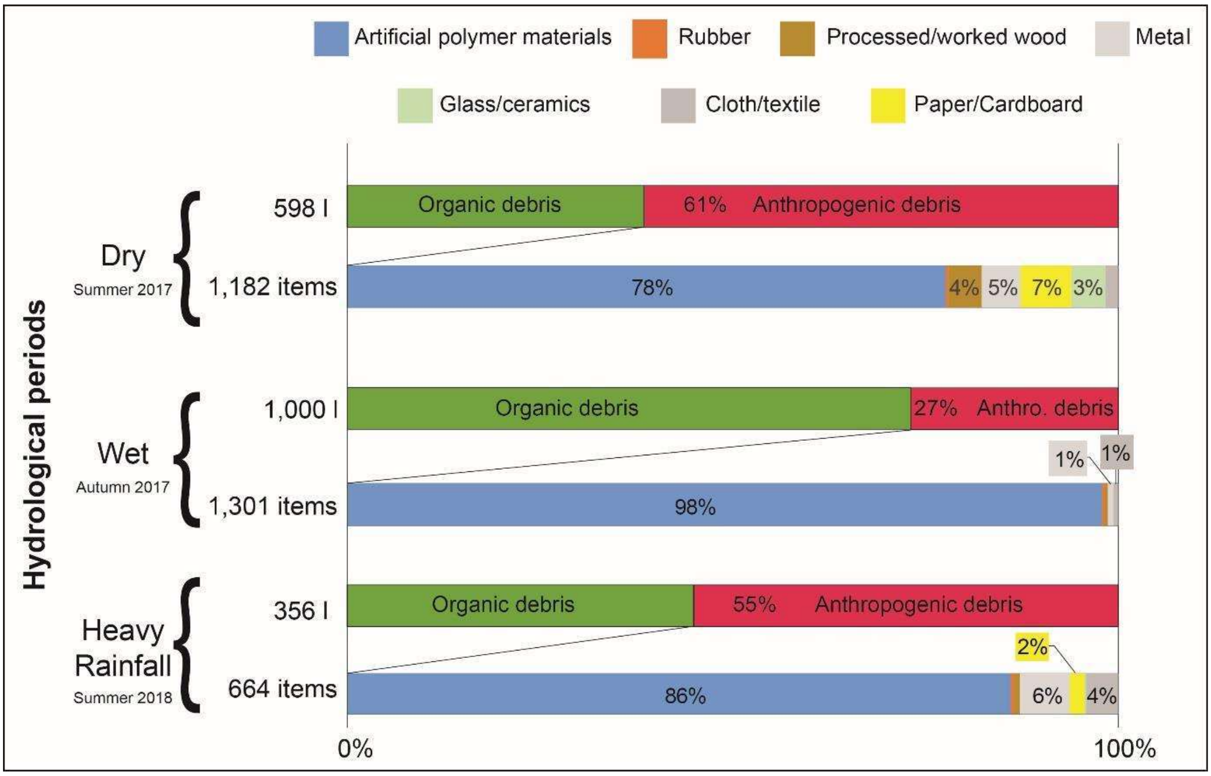

Figure 4: Composition of the screened materials sampled in Pugette for dry, wet and heavy rainfall period. Organic *vs* anthropogenic debris are based on volume percentages. Composition of anthropogenic litter is based on count according to the OSPAR/TSG-ML classification.

Type of anthropogenic debris

A total of 3147 litter items were sorted and counted according to OSPAR/TSG-ML classification (MSFD Technical Subgroup on Marine Litter, 2013) for dry (n =1,182), wet (n= 1,301) and heavy rainfall periods (n=664). All data are reportede in **"Screened material" in sup. Data**. Results show that anthropogenic waste is mostly composed of plastic debris (83% on average) recorded as "artificial polymer materials" (**Figure 4**), in agreement with González-Fernández et al. (2021) who reported similar results for European rivers with 82% plastic items. The fraction of plastic debris ranges between 78% during the dry period and 98% during the wet period. Other types of material correspond to minor fractions with glass/ceramics (0 – 3%), metal (1 – 6%), paper/cardboard (0 – 7%), processed wood (0 – 4%), cloth/textile (1 – 4%) and rubber (0 – 1%). Low proportions of those litter types are most likely the result of "washing" by the water that disintegrates paper/cardboard, while metal, glass and textiles may sink. This is supported by higher proportions of those materials (16% glass, 13% paper, 11.5% metal) found on riverbanks in Germany rivers by schoolchildren following a wide citizen sciences program (Kiessling et al., 2019). Littering was mostly attributed to recreational activities, suggesting local sources, rather than remote sources related to riverine transport and subsequent washing/sorting processes.

Screened anthropogenic debris during the wet period are characterized by a lower diversity in the types of material when compared to the dry period (**Figure 4**). But dumpsters filled up 4 – 6 times faster during the wet period (3.4 m^3/d) than during the dry period (0.9 m^3/d; **Table 1**), suggesting enhanced transport of riverine litter, including different types of material and organic debris. The highest rate of filling corresponds to the heavy rainfall event (9.3 m^3/d), which shows an intermediate diversity regarding types of material.

Top 10 specific items

The most abundant specific items commonly featuring in the Top 10 of dry (64% of total), wet (83% of total) and heavy rainfall periods (74% of total) are (i) unidentified plastic pieces between 2.5 and 50 cm (G79), (ii) food wrappings with crisps packets/sweet wrappers (G30), and (iii) food containers (G10). Tobacco-related products (G25, G26 or G27) and drink bottles (G7 or G8) are also present in all Top 10 specific items. However, small items able to pass through bar screens (i.e. < 3 cm) such as cigarette butts/filter (G27), plastic pieces < 2.5 cm (G78) or polystyrene pieces < 2.5 cm (G81) are only found in Top 10 for wet and heavy rainfall periods (**Figure 5**). This hydrological-related pattern suggests that cigarette butts could be considered as a marker of urban runoff. Alternatively, this pattern may be related to clogging with organic material with higher water flow and enhanced riverine litter transport. This is supported by results obtained in a sub-basin of the greater Paris area where most of the cigarette butts from urban runoff were collected by 1 cm bar screens, despite a previous screening of 6 cm (Treilles et al., 2021). Thus, fast clogging during wet periods may act as narrower bar screens, whereas small items are not collected during dry periods, when clogging is less likely.

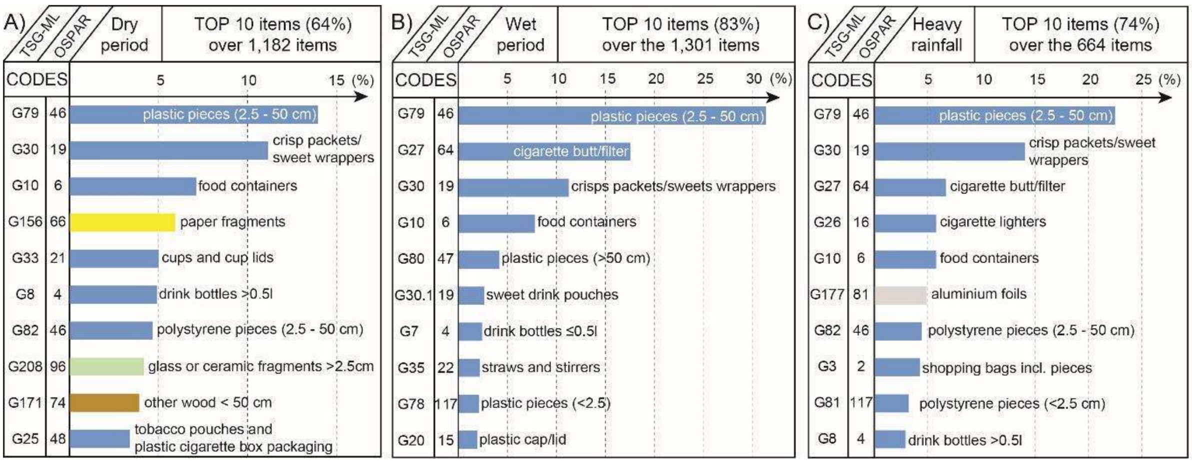

Figure 5: Top 10 items collected during dry, wet and heavy rainfall periods.

Those results are in line with other studies in rivers across Europe showing that unidentified plastic fragments (2.5–50 cm) and Single Use Plastics (i.e. bags, bottles and other packaging) are among the most abundant specific items (González-Fernández et al., 2021). Treilles et al. (2021) reported similar results in urban runoff with top specific items corresponding to plastic bags/films, crisp packets/sweet wrappers, cigarette butts, plastic fragments, garbage bags, foil wrappers, tampon applicators, plastic cups and medical items such as bandages. The latter is however not common to other studies and remain a local exception.

Economic sectors

When possible, identified specific items were assigned to their respective economic sectors (**Figure 6; see "Economic sectors" in sup. data**). Item counts were extrapolated to the whole dumpster for each sample (see section 2.3) and aggregated to get a clear overview of the economic sectors they correspond to. It yields 120,879 specific items in which 40.9% were not assigned to an economic sector because they were classified as "fragments" or ambivalent categories. The first identified economic sector is food (38.3%), including all type of food packaging (G7, G8, G10, G20, G24, G30, G33, G150, G151, G159, G175 to G178, G200) and other related accessories like straws, stirrers (G35), lolly sticks (G31), cutlery and trays (G34). The second economic sector is related to tobacco products (12.1%), including cigarette butts and filters (G27), lighters (G26), plastic cigarette box packaging (G25), and cigarette boxes (G152). Then, comes the sanitary sector (4.0%) with a sewage component, which includes wet wipes (G145), cotton bud sticks (G95), sanitary towels (G96), and a hygiene-related component like cosmetic containers (G11) and diverse household products (G29, G39, G98). Other textiles (G135 to G145, including wet wipes) and leisure and outdoor activities (G32, G90, G125 and G126) correspond to 3.5% and 1.1% of all specific items, respectively. Most food and tobacco products are related to packaging, which roughly corresponds to 50% of the specific items. Those results are in line with data compiled by Schwarz et al.(2019), showing packaging-related products represent up to 75% of the items in rivers followed by household products (2.5%), which may roughly correspond to sanitary, household and leisure and outdoor activities in our study. Comparisons remain difficult because there is no clear correspondence in literature between a specific item category and an economic sector. This may be solve in future by the recently updated and harmonized Joint List of categories at the European scale that unambiguously reports corresponding sources and economic sector for each specific item category (https://mcc.jrc.ec.europa.eu/main/dev.py?N=41&O=459).

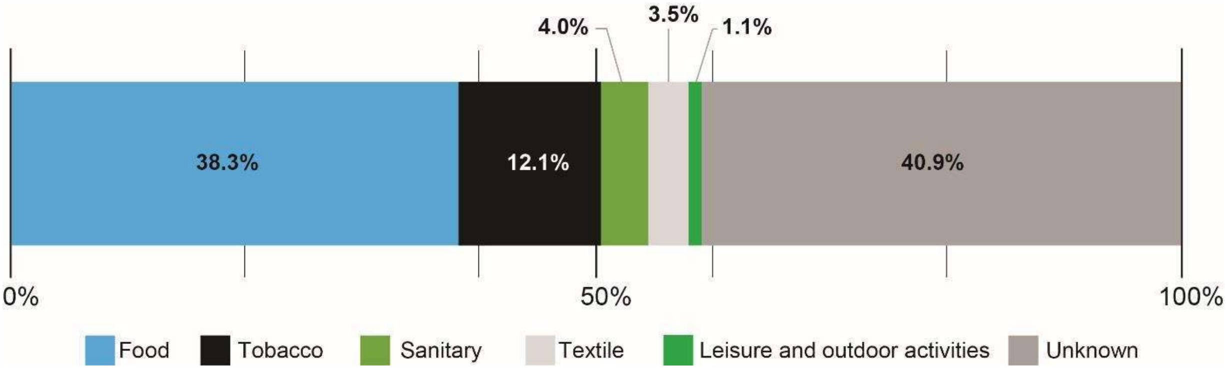

Figure 6: Litter composition relative to economic sectors over the extrapolated 120,879 specific items. An unknown category was added for items that were identified as "fragment" or with ambivalent categories regarding economic sectors. See text for the detailed specific items assigned to an economic sector.

The tobacco sector is the second identified economic sector despite a low diversity of the related specific items when compared to other economic sectors. This sector is of major concern because smokers exhibit a much greater propensity (65% of the smokers) to litter cigarette butts than other litter (Schultz et al., 2013). Then, they are easily transferred to the environment through stormwater systems with potential release of toxic chemicals (Weideman et al., 2020; Treilles et al., 2021). Furthermore, their small size prevents a satisfied level of recovery once they are released in the environment, but it also complicates their reliable monitoring. Visual counting on rivers are probably not suitable for catching the tobacco-related pollution because none of their representative categories entered the Top 20 floating riverine litter of European rivers (González-Fernández et al., 2021). In contrast, cigarette filters were found on riverbanks in the Top 20 riverine litter in the Meuse River (Van Emmerik et al., 2020), but also on Chilean and German riverbanks representing 11% and 20% of all litter, respectively (Kiessling et al., 2019; Honorato-Zimmer et al., 2021). They also represented 24% of the collected litter <6 cm in stormwater in a small peri-urban basin (Treilles et al., 2021). Tobacco-related products are then everywhere in the aquatic environment and concern both direct littering and litter transport by stormwater. This problematic calls for a better information focused on changing behavior of the concerned people as suggested by Ryan et al. (2020) who note even a national ban on tobacco sales during the pandemic of Covid-19 did not result in decrease of cigarette butts in urban streets of Durban, South Africa: 33% litter were tobacco-related products by counts over there at that time.

3.2. Quantitative assessment

The quantitative assessment of the riverine litter in the Huveaune River is limited to an estimated number of items per dumpster for three distinct hydrological periods: dry, wet and heavy rainfall period (**see "Litter load" in sup. Data for details**). An accumulation rate of item per day in dumpsters was calculated based on extrapolated counts for each period. Because the entire river section is screened, the number of items accumulated per day roughly corresponds to the number of items flowing in the rivers per day, apart from litter passing through bar screens or bypassed, which is not quantifiable by nature. Thus, the following results for wet and heavy rainfall periods are conservative.

When considering all categories of litter items, 1,782 litter items/day (1,383 plastics/day) flew in the Huveaune River during the dry period, 4,461 litter items/day (4,367 plastics/day) during the wet periods and 17,408 litter items/day (14,971 plastics/day) during the heavy rainfall episode. These results are equivalent to 74 litter items/h (dry period) to 725 items/h (heavy rainfall episode) and fall into the upper range of the floating litter fluxes estimated for the 17 rivers ranging into the small to medium basin category (100–10,000 km^2) reported by González-Fernández et al. (2021). Small and mountainous Chilean rivers also show relatively low floating litter flow, when compared to the Huveaune River, with 10.1 litter items/h (Honorato-Zimmer et al., 2021). This is probably the result of underestimation of litter by visual counting, especially during extreme events that are often missing in the literature. In contrast, our methodology considers the whole water column and extreme events.

Nevertheless, according to van Calcar and van Emmerik (2019) who reported visual counting of floating plastic items only, the Huveaune River falls into the range of the Seine River corresponding to the upper range of European rivers and lower range of Asian rivers, roughly 2,000–20,000 items/d.

When extrapolated to a year and weighted relative to the mean fraction of time corresponding to dry, wet and heavy rainfall periods, it yields 841,927 items/yr in which 83% are plastic debris. A number to mass conversion must be applied to estimate a mass flow. The range of 1–5 (1.0 to 5.3 g/macroplastic) constitutes the confidence interval regarding our mass flow estimates of macroplastic debris. According to **equation 1**, the mass flow of plastic debris would range between 0.7 and 3.7 mt/yr, which is equivalent to 1.4–7.2 g/cap/yr when considering the population upstream Pugette only, i.e. 512,000 inhabitants (**see "Litter load" in sup data**). Notice this estimate is the quantity of macroplastics which does not reach the sea because it is collected by bar screens and ends up in dumpsters for appropriate treatment. We acknowledge that the absence of replicates among the three hydrological periods rules out variability estimations between them, which might influence the final mass flow estimate. However, one may argue that each sample integrates a part of this variability, because samples correspond to 21, 7 and 3 days of litter accumulation for dry, wet and heavy rainfall, respectively, which is equivalent to 31 days of sampling, i.e. 8% a year. This is tremendously higher than visual counting on European rivers reported by González-Fernández et al. (2021), corresponding to 410 h counting on 42 rivers, i.e. 0.1% a year per river on average. In addition, authors acknowledged the lack of extreme events like heavy rainfall episodes or floods in their data. By covering contrasting hydrological periods over days, we believe that extrapolation to the annual scale is feasible, and probably more robust than studies that do not consider extreme events. But, annual estimates must be used with caution like others in literature, we should say.

This approach, which in turn considers mass flows of plastic debris as a function of dry, wet and heavy rainfall periods, also enables to estimate the relative contribution of each hydrological period in the total annual mass flow. So, 63.3% of the total mass flow of macroplastic debris may occur during dry periods, 25.3% during wet periods and 11.4% during heavy rainfall episodes. Thus, wet periods and even more heavy rainfall episodes contribute to the mass flow much more than dry periods relative to their respective timespan, i.e. 87.5%, 11.1% and 1.5% of the year for dry, wet and heavy rainfall periods, respectively. Those findings support the fact that macroplastic transport exhibits a strong seasonality (van Emmerik et al., 2019). Beyond clear seasonality, our study shows the impact of a single rainfall event with flash flood events probably being major drivers of the plastic transport as suggested by models in more affected regions of the world along with the ongoing global warming (Roebroek et al., 2020). Similar conclusions were drown in Chile at the national level from their fast flowing mountain rivers that may rapidly flush litter downstream with important fragmentation during transport, especially during high water discharge (Honorato-Zimmer et al., 2021).

3.3. How much plastics finally reach the sea?

This question often arises when the baseline data come from litter collections either by hand on riverbanks (Tramoy et al., 2021) or by passive technical devices (van Emmerik and Schwarz, 2020), and so the estimated amount of plastics correspond to the fraction which does not reach the sea. Even visual counting must face this question if they are performed far away from the river mouth, because growing evidences show that up- to downstream transport of plastic debris is not linear. They are rather dominated by stochastic processes, especially at the land-ocean interface under tidal influence (Liro et al., 2020; Tramoy et al., 2020a, 2020b; Dris et al., 2022). When compared to visual counting or floating booms in Paris megacity that only capture floating debris (Gasperi et al., 2014), bar screens are also able to capture non-floating debris depending on their size. However, it does not provide direct evidences on the plastic leakage into the sea.

In this paper, we propose a way to estimate the plastic emission into the sea based on the volume of water overflowing toward the sea and its mass concentrations in macroplastic. A mean quantity of macroplastics can be estimated for each hydrological periods of measurement relative to the volume of water, which is bar screened (either at 3 cm or 7 cm), leading to a mass concentration of macroplastics in water. It yields 17 – 86 mg/m^3 for the dry period, 46 – 232 mg/m^3 for the wet period and 65 – 324 mg/m^3 for the heavy rainfall period (**see ”Litter load” in sup data**). The latter concentration is applied to the volume of water bypassed toward the Prado Beach and the Sea, i.e 6.2 10^6 m^3/yr on average over 2018/2019 (**see “Water flow” in sup data**). It yields 0.4 – 2.0 mt/yr, which is equivalent to 0.8 – 3.9 g/cap/yr of macroplastic debris entering the Sea through the Huveaune River. It can be considered that almost all this quantity will reach the sea instantaneously after overflow, because the channel between Pugette and the Prado Beach is only 2 km long, straight and water flow during those episodes are at least 10 times higher than the average water flow. Also, there are no tides able to push debris back on lands (e.g. Tramoy et al., 2020b). This estimate is on average two times higher than the modelled estimate of González-Fernández et al. (2021) that yield between 41,719 and 247,961 items (lowest and highest values), in which 82% of them were plastics, i.e. 0.05 and 1.3 mt/yr (for 1.0 to 5.3 g/macroplastic). Although in the same order of magnitude, this model may yield more conservative estimates than ours because it only considers floating macroplastics and avoids extreme events. The estimate of 0.4 – 2.0 mt/yr of macroplastics reaching the Sea through the Huveaune River should be added to the previous mass flow estimated in the bar screens, because it corresponds to the “unseen” plastic mass that is not captured by bar screens. Finally, the total mass flow of plastic debris transiting in the Huveaune

River is 1.1–5.7 mt/yr, equivalent to 2.1–11.1 g/cap/yr. Thus, the removal efficiency of litter by bar screen is about 65%, whereas 35% is bypassed directly into the sea.

3.4. From global models to local field studies

Local field studies are used to calibrate and validate global models (e.g. Lebreton et al., 2017; Schmidt et al., 2017; González-Fernández et al., 2021; Meijer et al., 2021). Those field studies must use the same methodology. They are often based visual counting for macroplastics. The use of alternative holistic approaches based on ground-truth data like in this work for plastic flux estimations does not help to better calibrate global models, but come challenging their validity and questioning their results. Figure 7 shows a synthetic comparison between macroplastic mass flows estimated in the Huveaune River (**Figure 7A**) and in the Seine River (**Figure 7B**), which is based on another holistic approach (Tramoy et al., 2021). Mismanaged Plastic Waste (MPW) are also represented and were estimated according to Jambeck et al. (2015) to enable comparisons with other studies using MPW as an indicator. Annual plastic emissions into the sea correspond to 0.1–0.3% of the total MPW generated in the Huveaune watershed and 0.5–1.0% in the Seine watershed (**Figure 7**; Tramoy et al., 2021). As noticed and discussed for the Seine River, but also for other European rivers, Jambeck'approach (MPW indicator) overestimates the input of plastics into rivers and into the Ocean by one to two orders of magnitude and/or the vast majority of plastic debris are removed before reaching the sea or accumulate on lands and river banks (e.g. Castro-Jiménez et al., 2019; Schöneich-Argent et al., 2020; Vriend et al., 2020; Tramoy et al., 2021). Refining global models of plastic export as recently proposed by Meijer et al. (2021) is required. These authors refined global annual emissions of plastics (excluding microplastics) with estimates ranging between 0.8 million and 2.7 million metric tons per year. For France, they estimated 0.85% MPW were emitted into the Ocean through rivers, not too different from what we found in the

Huveaune River or in the Seine River. Most importantly, they shed new lights on the relative contribution of huge and small rivers showing that small urban rivers, especially in South East Asia, were the most contributing rivers to the worldwide plastic pollution. The model developed by González-Fernández et al. (2021) came to the same conclusions for small coastal basins (<100 km^2) in Europe, suggesting that small basins are more efficient in transporting litter to the sea than large rivers.

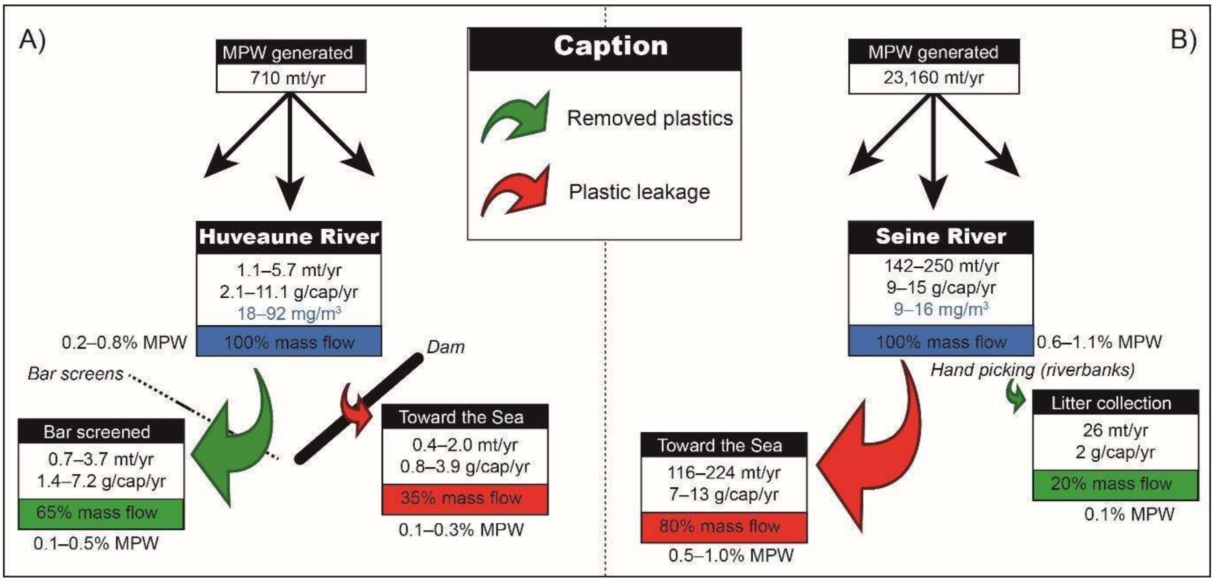

Figure 7: Synthesis of the macroplastic mass flows in the Huveaune River (A) and the Seine River (B). Data from the Seine River are based on Tramoy et al. (2021). MPW calculations are recalculated based on Jambeck et al. (2015) with a MPW generation in France of 0.0038 kg/cap/d (1,387 g/cap/yr), 512,000 inhabitants in the Huveaune watershed and 16,700,000 in the Seine watershed.

When mass flows of plastic debris estimated in the Huveaune River or in the Seine River are normalized to the population of the watershed, results converge to a similar order of magnitude of 10 g/cap/yr (**Figure 7**). It decreases to ~1 g/cap/yr for the Huveaune River when only plastic emissions into the sea are considered. At the European scale, annual plastic emissions of floating macroplastics are in the range 1–10 g/cap/yr (González-Fernández et al., 2021). Those authors found roughly 1,500–5,000 mt/yr of macroplastics are entering into the seas through >30,000 rivers (including small basins <100 km^2), which is equivalent to 2–7 g/cap/yr for 694 million inhabitants in Europe included in their mean-based estimate. Notice that strong heterogeneities exist within Europe with for example German rivers showing plastic emissions ranging between 0.04 and 0.5 g/cap/yr in the Ems River, 0.01 and 0.6 g/cap/yr in the Weser River, and 0.06 and 16.1 g/cap/yr in the Elbe River, even though estimates also included plastic debris on riverbanks, riverbed and water column (Schöneich-Argent et al., 2020, 2021; **see "Lit. data" in sup. data**).

At the basin scale, the main difference between the Huveaune River and the Seine River lies in the respective fraction of litter collected and returned to the waste management system, i.e. 65% of the annual macroplastic mass flow is removed by bar screens, whereas this fraction falls to 20% in the Seine River with hand collection of litter on estuarine riverbanks. However, the anthropogenic pressure normalized to the surface of the Huveaune watershed (~1,100 cap/km^2) is much stronger than in the Seine watershed (~200 cap/km^2), with a much lower dilution effect in the Huveaune River (~2 m^3/s), than in the Seine River (~500 m^3/s). This makes the plastic pollution much more visible for local residents in the Huveaune River than in the Seine River. Then, there is a citizen demand to “solve” this visual disorder of riverine litter. Redirecting polluted water with grey infrastructures, such as giant bar screens at Pugette station for better waste management, partly respond to this demand (communication by SERAMM, https://madeinmarseille.net/52854-seramm-dernier-kilometre-huveaune/).

This task becomes almost impossible during heavy rainfall and storm events. Despite their relative efficiency for collecting riverine litter most of the time, grey infrastructures like giant bar screens are not trivial. It requires anthropizing an entire section of river with many cubic meters of concretes, thus sacrificing ecological continuity. In addition, this does not solve (i) the upstream dissemination of riverine litter and thus the induced visible pollution for residents, (ii) the transport of smaller plastic debris than the bar screens spacing, or (iii) flash flood-related riverine litter which is bypassed to the sea. In addition, 585 ± 138 mt/yr of riverine litter, on average, are dumped from bar screens in Pugette and from the other similar structure settled on the Aygalades, a tiny waterway North of Marseille (SERAMM, pers. Com.). This means that hundreds metric tons of organic litter that was supposed to be flushed into the sea – probably supporting marine life and natural ecosystem cycles – are removed to remove few metric tons of plastic debris each year. Separating organic litter for composting and anthropogenic litter for recycling is furthermore not economically valuable, so all litter is locally dumped into landfills. This extreme anthropization and its consequences finally raises questions about "sustainable" development policies in urban areas and our society's relationship with nature (e.g. Rowiński et al., 2018). This question is beyond environmental cost/benefit analysis, even though other parameters than riverine litter are sometimes considered such as: biodiversity, ecological continuity, flood risk, river ecosystem services or river transport activities.

4. Concluding remarks

A grey infrastructure is settled at Pugette on the Huveaune River, a small urban river in Marseille, South of France, for redirecting water through bar screens and a pipe to prevent litter occurrence on the highly frequented Prado beach, 2 km westward. Opportunistic grab sampling together with high frequency monitoring of water flow from the structure manager SERAMM enabled to characterize riverine litter polluting the river and eventually reaching the Sea. Plastics referred to as artificial polymer in the OSPAR/TSG-ML classification corresponded to 83% (by count) of the total riverine litter. The main categories previously reported in European rivers are fragments and single-use items (e.g. bottles, food wrappers and packaging, bags) and the Huveaune River is no exception. Tobacco-related single-use products are also abundantly represented in our data in contrast to data coming from visual counting, probably because cigarette butts – which are dominant in stormwaters – are invisible to observers and/or already fragmented into fibers, or sunk below the water surface. Notice that economic sectors and litter sources will be unambiguously reported in future works with the recently updated and harmonized Joint List of categories at the European scale (https://mcc.jrc.ec.europa.eu/main/dev.py?N=41&O=459).

Among the 1.1–5.7 mt/yr (equivalent to 2.1–11.1 g/cap/yr) of macroplastics flowing in the Huveaune River, 0.4–2.0 mt/yr (equivalent to 0.8–3.9 g/cap/yr) may reach the sea during heavy rainfall episodes. Before the bar screens, the amount of plastic per capita is of the same order of magnitude as the amounts in the Seine River and in other European rivers, although large heterogeneities exist within Europe. After the bar screens, 65% of the riverine litter is removed and returned to classical waste management system, i.e. controlled landfills. Only heavy rainfalls may transfer riverine litter to the Sea. Thus, grey infrastructures as technical solutions will never be sufficient to reach the goal of zero plastic emission into the sea, because they cannot contain extreme meteorological events. In additions, they break the ecological continuity and prevent organic debris to feed the marine realm.

The Huveaune River is a typical study case showing a non-negligible and uncontrolled leakage of riverine litter remains, despite all recovery systems implemented in well-developed countries like in France. As suggested by González-Fernández et al. (2021), this supports prevention policies rather than end-of-pipe solutions and production/use regulations on a global scale as well as economic-social innovations focused on changes in consumption habits and behaviors. Most recently, UN made similar recommendations for tackling marine litter on a global scale with a systemic approach including (i) the need to translate words into actions, (ii) more regulations at national scales and coordination on a global scale, (iii) immediate implementation of a circular plastic economy (e.g. reduce, reuse, repair, replace, recycle), (iv) better regulation and transparency of the international trade in plastic waste to protect people and nature with the Basel Convention as an important initial step, and (v) developing better and more harmonized monitoring strategies that are capable to evaluate the impact of marine litter policies (UN Environment Programme, 2021). The last recommendation should be achieved by implementing monitoring in routine use in different environmental compartments from sources (i.e., urban areas) to receiving environments (i.e. rivers and ocean), with common baselines like the OSPAR/TSG-ML classification and its updates. The use of existing infrastructures like the bar screens in the Huveaune River should then be considered as monitoring tools.

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6. References

Castro-Jiménez, J., González-Fernández, D., Fornier, M., Schmidt, N., Sempéré, R., 2019. Macro-litter in surface waters from the Rhone River: Plastic pollution and loading to the NW Mediterranean Sea. Mar. Pollut. Bull. 146, 60–66. https://doi.org/10.1016/j.marpolbul.2019.05.067

Dris, R., Tramoy, R., Alligant, S., Gasperi, J., Tassin, B., 2022. Plastic debris flowing from rivers to oceans: the role of the estuaries as a complex and poorly understood key interface, in: Handbook of Microplastics in the Environment. Sringer International Publishing.

Gasperi, J., Dris, R., Bonin, T., Rocher, V., Tassin, B., 2014. Assessment of floating plastic debris in surface water along the Seine River. Environ. Pollut. 195, 163–166. https://doi.org/10.1016/j.envpol.2014.09.001

González-Fernández, D., Cózar, A., Hanke, G., Viejo, J., Morales-Caselles, C., Bakiu, R., Barceló, D., Bessa, F., Bruge, A., Cabrera, M., Castro-Jiménez, J., Constant, M., Crosti, R., Galletti, Y., Kideys, A.E., Machitadze, N., Pereira de Brito, J., Pogojeva, M., Ratola, N., Rigueira, J., Rojo-Nieto, E., Savenko, O., Schöneich-Argent, R.I., Siedlewicz, G., Suaria, G., Tourgeli, M., 2021. Floating macrolitter leaked from Europe into the ocean. Nat. Sustain. 4, 474–483. https://doi.org/10.1038/s41893-021-00722-6

Honorato-Zimmer, D., Kiessling, T., Gatta-Rosemary, M., Kroeger Campodónico, C., Núñez-Farías, P., Rech, S., Thiel, M., 2021. Mountain streams flushing litter to the

sea – Andean rivers as conduits for plastic pollution. Environ. Pollut. 291, 118166. https://doi.org/10.1016/j.envpol.2021.118166
Ivar do Sul, J.A., Costa, M.F., Silva-Cavalcanti, J.S., Araújo, M.C.B., 2014. Plastic debris retention and exportation by a mangrove forest patch. Mar. Pollut. Bull. 78, 252–257. https://doi.org/10.1016/j.marpolbul.2013.11.011
Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347, 768–771. https://doi.org/10.1126/science.1260352
Kanzari, F., Syakti, A.D., Asia, L., Malleret, L., Piram, A., Mille, G., Doumenq, P., 2014. Distributions and sources of persistent organic pollutants (aliphatic hydrocarbons, PAHs, PCBs and pesticides) in surface sediments of an industrialized urban river (Huveaune), France. Sci. Total Environ. 478, 141–151. https://doi.org/10.1016/j.scitotenv.2014.01.065
Kiessling, T., Knickmeier, K., Kruse, K., Brennecke, D., Nauendorf, A., Thiel, M., 2019. Plastic Pirates sample litter at rivers in Germany – Riverside litter and litter sources estimated by schoolchildren. Environ. Pollut. 245, 545–557. https://doi.org/10.1016/j.envpol.2018.11.025
Lau, W.W.Y., Shiran, Y., Bailey, R.M., Cook, E., Stuchtey, M.R., Koskella, J., Velis, C.A., Godfrey, L., Boucher, J., Murphy, M.B., Thompson, R.C., Jankowska, E., Castillo, A.C., Pilditch, T.D., Dixon, B., Koerselman, L., Kosior, E., Favoino, E., Gutberlet, J., Baulch, S., Atreya, M.E., Fischer, D., He, K.K., Petit, M.M., Sumaila, U.R., Neil, E., Bernhofen, M.V., Lawrence, K., Palardy, J.E., 2020. Evaluating scenarios toward zero plastic pollution. Science. https://doi.org/10.1126/science.aba9475
Lebreton, L.C.M., van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. Nat. Commun. 8, 15611. https://doi.org/10.1038/ncomms15611
Liro, M., Emmerik, T. van, Wyżga, B., Liro, J., Mikuś, P., 2020. Macroplastic Storage and Remobilization in Rivers. Water 12, 2055. https://doi.org/10.3390/w12072055
Meijer, L.J.J., Emmerik, T. van, Ent, R. van der, Schmidt, C., Lebreton, L., 2021. More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Sci. Adv. 7, eaaz5803. https://doi.org/10.1126/sciadv.aaz5803
MSFD Technical Subgroup on Marine Litter, 2013. Guidance on Monitoring of Marine Litter in European Seas.
Roebroek, C., Harrigan, H., van Emmerik, T., Baugh, C., Eilander, D., Prudhomme, C., Pappenberger, F., 2020. Plastic in global rivers: are floods making it worse? https://doi.org/10.21203/rs.3.rs-43330/v1
Rowiński, P.M., Västilä, K., Aberle, J., Järvelä, J., Kalinowska, M.B., 2018. How vegetation can aid in coping with river management challenges: A brief review. Ecohydrol. Hydrobiol., SI: Ecohydrology for the Circular Economy and Nature-Based Solutions towards mitigation/adaptation to Climate Change 18, 345–354. https://doi.org/10.1016/j.ecohyd.2018.07.003
Ryan, P.G., Maclean, K., Weideman, E.A., 2020. The Impact of the COVID-19 Lockdown on Urban Street Litter in South Africa. Environ. Process. 7, 1303–1312. https://doi.org/10.1007/s40710-020-00472-1
Schmidt, C., Krauth, T., Wagner, S., 2017. Export of Plastic Debris by Rivers into the Sea. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.7b02368
Schöneich-Argent, R.I., Dau, K., Freund, H., 2021. Corrigendum to "Wasting the North Sea? – A field-based assessment of anthropogenic macrolitter loads and emission rates of three German tributaries" [Environ. Pollut. 263 (Part B) (August 2020) 114367]. Environ. Pollut. 287, 117235. https://doi.org/10.1016/j.envpol.2021.117235

Schöneich-Argent, R.I., Dau, K., Freund, H., 2020. Wasting the North Sea? – A field-based assessment of anthropogenic macrolitter loads and emission rates of three German tributaries. Environ. Pollut. 263, 114367. https://doi.org/10.1016/j.envpol.2020.114367

Schultz, P.W., Bator, R.J., Large, L.B., Bruni, C.M., Tabanico, J.J., 2013. Littering in Context: Personal and Environmental Predictors of Littering Behavior. Environ. Behav. 45, 35–59. https://doi.org/10.1177/0013916511412179

Schwarz, A.E., Ligthart, T.N., Boukris, E., van Harmelen, T., 2019. Sources, transport, and accumulation of different types of plastic litter in aquatic environments: A review study. Mar. Pollut. Bull. 143, 92–100. https://doi.org/10.1016/j.marpolbul.2019.04.029

Tramoy, R., Gasperi, J., Colasse, L., Silvestre, M., Dubois, P., Noûs, C., Tassin, B., 2020b. Transfer dynamics of macroplastics in estuaries – New insights from the Seine estuary: Part 2. Short-term dynamics based on GPS-trackers. Mar. Pollut. Bull. 160, 111566. https://doi.org/10.1016/j.marpolbul.2020.111566

Tramoy, R., Gasperi, J., Colasse, L., Tassin, B., 2021. Transfer dynamic of macroplastics in estuaries — New insights from the Seine estuary: Part 3. What fate for macroplastics? Mar. Pollut. Bull. https://doi.org/sous presse

Tramoy, R., Gasperi, J., Colasse, L., Tassin, B., 2020a. Transfer dynamic of macroplastics in estuaries — New insights from the Seine estuary: Part 1. Long term dynamic based on date-prints on stranded debris. Mar. Pollut. Bull. 152, 110894. https://doi.org/10.1016/j.marpolbul.2020.110894

Treilles, R., Gasperi, J., Saad, M., Tramoy, R., Breton, J., Rabier, A., Tassin, B., 2021. Abundance, composition and fluxes of plastic debris and other macrolitter in urban runoff in a suburban catchment of Greater Paris. Water Res. 192, 116847. https://doi.org/10.1016/j.watres.2021.116847

UN Environment Programme, 2021. Policy Options to Eliminate Additional Marine Plastic Litter.

van Calcar, C.J. van, van Emmerik, T.H.M. van, 2019. Abundance of plastic debris across European and Asian rivers. Environ. Res. Lett. 14, 124051. https://doi.org/10.1088/1748-9326/ab5468

van Emmerik, T., Kieu-Le, T.-C., Loozen, M., van Oeveren, K., Strady, E., Bui, X.-T., Egger, M., Gasperi, J., Lebreton, L., Nguyen, P.-D., Schwarz, A., Slat, B., Tassin, B., 2018. A Methodology to Characterize Riverine Macroplastic Emission Into the Ocean. Front. Mar. Sci. 5. https://doi.org/10.3389/fmars.2018.00372

Van Emmerik, T., Roebroek, C., Winter, W. de, Vriend, P., Boonstra, M., Hougee, M., 2020. Riverbank macrolitter in the Dutch Rhine–Meuse delta. Environ. Res. Lett. 15, 104087. https://doi.org/10.1088/1748-9326/abb2c6

van Emmerik, T., Schwarz, A., 2020. Plastic debris in rivers. WIREs Water 7, e1398. https://doi.org/10.1002/wat2.1398

van Emmerik, T., Strady, E., Kieu-Le, T.-C., Nguyen, L., Gratiot, N., 2019. Seasonality of riverine macroplastic transport. Sci. Rep. 9, 1–9. https://doi.org/10.1038/s41598-019-50096-1

Vriend, P., van Calcar, C., Kooi, M., Landman, H., Pikaar, R., van Emmerik, T., 2020. Rapid Assessment of Floating Macroplastic Transport in the Rhine. Front. Mar. Sci. 7. https://doi.org/10.3389/fmars.2020.00010

Weideman, E.A., Perold, V., Arnold, G., Ryan, P.G., 2020. Quantifying changes in litter loads in urban stormwater run-off from Cape Town, South Africa, over the last two decades. Sci. Total Environ. 724, 138310. https://doi.org/10.1016/j.scitotenv.2020.138310