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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

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

33

34 **1. Introduction**

35 “Marine plastic litter entering the ocean is increasing, the impacts of plastic pollution on
36 marine and coastal ecosystems are worsening, and our increasing understanding of the negative
37 impacts of plastic pollution on human health is creating greater urgency to act.” This is how
38 the last UN report commissioned by the G20 (UN Environment Programme, 2021) introduces
39 the problem, sounding the alarm on the uncontrolled leakage of plastics into the ocean which
40 is thought to triple by 2040 (Lau et al., 2020). On a global scale, plastic emissions into the
41 Ocean reach 0.8 – 2.7 million metric tons per year (mt/yr) according to the most recent model
42 of riverine plastic export (Meijer et al., 2021). Those authors refined global annual emissions
43 of plastics (excluding microplastics) based on Mismatched Plastic Waste (MPW) generation
44 calibrated with and validated by field studies using visual counting across the world (mostly
45 Europe and Asia). In contrast to previous models suggesting few rivers were responsible for
46 80% of the global plastic emissions (e.g. Lebreton et al., 2017; Schmidt et al., 2017), Meijer et
47 al. (2021) concluded that this proportion rather corresponds to more than 1,000 rivers most of
48 which are small urban rivers in South East Asia. At the European scale, another modeling
49 approach based on a wide database of riverine floating macrolitter (>2.5 cm) also recognized
50 the relative importance of small basins (<100 km²) close to coastlines (González-Fernández et

51 al., 2021). Their model highlighted well-developed countries as non-negligible sources of
52 riverine litter despite an improved waste management and well-developed recovery systems.
53 These considerations highlight the need of critical case studies in river basins where those
54 recovery systems are used.

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

67 In this study, another indirect approach was applied in the Huveaune River in Marseille
68 (870,000 inhabitants, Southern France), based on existing grey infrastructures collecting
69 riverine litter over the whole water column. According to the International Institute for
70 Sustainable Development, “grey infrastructures involve engineered assets that provide one or
71 multiple services required by society, such as transportation or wastewater treatment”. In this
72 case, the grey infrastructure prevents riverine litter to reach the Mediterranean Sea close to the
73 highly frequented Prado beach. Nowadays, water is redirected to the south of Marseille (i.e.,
74 Cortiou) after being bar screened. Bar screens are passive technical devices, which capture
75 riverine litter as described for other type of passive devices by van Emmerik and Schwarz

76 (2020). When water flow is too high ($> 30 \text{ m}^3/\text{s}$), water overflows the dam to prevent damages
77 of infrastructures and is bypassed to the Prado beach without any treatment. The Huveaune
78 River is a small urban river of 50 km length ($\sim 2 \text{ m}^3/\text{s}$) and is known for its relative high
79 contamination in PCBs, a persistent organic pollutant, related to industrial and urban areas
80 (Kanzari et al., 2014), but also a constant visual pollution of macrolitter.

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

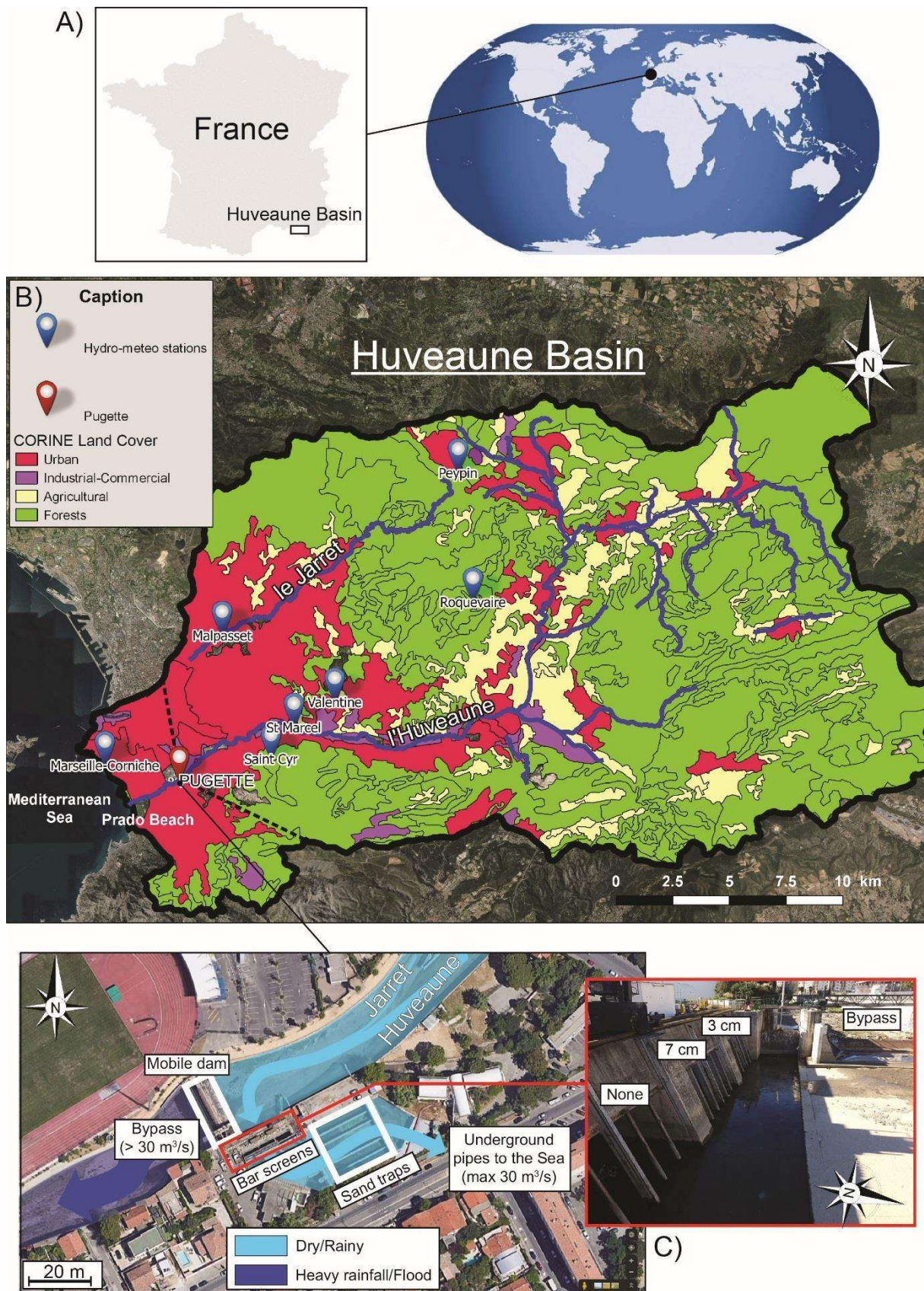
92

93 **2. Material and method**

94 **2.1. The Huveaune watershed**

95 The Huveaune watershed is located southern France (**Figure 1A**) and is 597 km^2 wide
96 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
97 in the Huveaune River, including bar screening, is performed by the company “Service
98 d'Assainissement Marseille Métropole” (SERAMM for Sewerage Service Marseille
99 Metropolis). The grey infrastructure asset consists in a dam with concrete dykes and a basic
100

101 water pre-treatment plant with bar screens and sand traps (**Figure 1C**). The whole water column
102 is passing through the infrastructure. The aim is to better manage the flood risk of the
103 downstream part of the river, but also to prevent beaching of riverine litter on the Prado Beach
104 or other pollutants to reach the Sea without treatment. Instead, treated water is redirected to the
105 Sea through underground pipes. Screened material is automatically collected, dumped and
106 managed by SERAMM for appropriate treatment. Water flow is monitored at a high frequency
107 (every hour), as well as overflows toward the Prado beach for reporting to the authorities. In
108 this study, Pugette is considered as the most downstream point of the Huveaune River. Based
109 on GIS analysis, 512,000 inhabitants are living in the Pugette Basin (see **“Pop. PugetteB” in**
110 **sup. Data**).



111

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

114 along its main course, with Marseille megacity downstream. Land cover is based on CORINE Land Cover-CLC12
115 (<https://www.statistiques.developpement-durable.gouv.fr/corine-land-cover-0?rubrique=348&dossier=1759>).
116 The water treatment plant of Pugette is located 2 km upstream the Prado beach which constitutes the outlet of the
117 Huveaune River. Pugette defines the basin limits for plastic mass flow calculation per capita (dashed lines). See
118 2.2 for details on the hydro-meteorological stations and their respective use. C) The water treatment plant in
119 Pugette is equipped with vertical bar screens of 3 cm and 7 cm spacing to prevent coarse anthropogenic debris to
120 reach the Mediterranean Sea. A bypass prevents damages and overflow on the structure during heavy rainfall
121 episodes ($\geq 30 \text{ m}^3/\text{s}$). Water is bar screened during dry and regular wet periods ($<10 \text{ m}^3/\text{s}$).

122

123 The dam lying on the main channel in Pugette acts as a bypass for water flow above 30
124 m^3/s to prevent damages to the structure during heavy rainfall episodes and consecutive flash
125 flood events (**Figure 1C**). The fraction of bypassed water directly flows into the sea, west of
126 Marseille, bringing all pollutants on the Prado beach and into the sea (**Figure 1B**). The Jarret
127 River is a tributary of the Huveaune River, which is partly underground until it flows into the
128 Huveaune River few meters before Pugette station. Screening of coarse material is performed
129 by passive technical devices at Pugette station using aligned automatic bar screens with spacing
130 of 3 cm and 7 cm (**Figure 1C**). All the material collected is routinely sent to landfills. The 3
131 cm bar screens always work. The 7 cm bar screens work with water flow above $5 \text{ m}^3/\text{s}$. Between
132 $10 \text{ m}^3/\text{s}$ and $30 \text{ m}^3/\text{s}$, water can escape through underground pipes toward the sea, south of
133 Marseille, without any screening. In fact, the excess water above $10 \text{ m}^3/\text{s}$ reaches the sea
134 without screening either to the south through pipes or to the Prado beach for the overflowed
135 fraction above $30 \text{ m}^3/\text{s}$.

136 Similar grey infrastructures do exist in another small waterway called Les Aygalades,
137 north of Marseille, but the riverine litter collected has been investigated for only one wet period,
138 while water flow is not currently monitored and population on the watershed not well
139 constrained. For those reasons, this sample has been ruled out. However, SERAMM reports

140 the mixed quantity of riverine litter collected by both infrastructures. It reaches 585 ± 138 mt/yr
141 over the period 2012-2019.

142

143 **2.2.Hydrology**

144 Over 2017 and 2018, the mean water flow in The Huveaune River is 2.4 ± 2.7 m³/s at
145 Pugette with a median value of 1.8 m³/s (min = 0.1 m³/s and max = 70.2 m³/s), which
146 corresponds to the sum of water flows recorded at Malpasset (the Jarret River) and at St Marcel
147 (The Huveaune River; **Figure 1B**). The year 2017 was particularly dry, while 2018 was
148 particularly wet (**Figure 2**). In order to determine the average time of dry, wet and heavy
149 rainfall periods over a mean year at the basin scale, we compiled the occurrence and magnitude
150 of daily precipitation recorded on the watershed at Marseille Corniche, Roquevaire and Peypin
151 stations in 2017 and 2018 (<https://www.infoclimat.fr/climato/>; **Figure 1B**). Based on the
152 precipitation alert thresholds in Pugette station (SERAMM, pers. Com), the daily precipitations
153 characterizing wet and heavy rainfall periods was set as follows: Dry < 2 mm ≤ wet > 30 mm
154 ≤ heavy rainfall periods. Hence, on average, the dry periods correspond to 87.5% of the time,
155 the wet periods to 11.1%, and the heavy rainfall periods to 1.5% over 2017 and 2018 (**See**
156 **“Precipitation” in sup data**). Volumes of water overflowed toward the Prado beach are
157 available for 2018 and 2019 with $6.2 \cdot 10^6$ m³/yr on average over the period (**See “Water flow”**
158 **in sup data**).

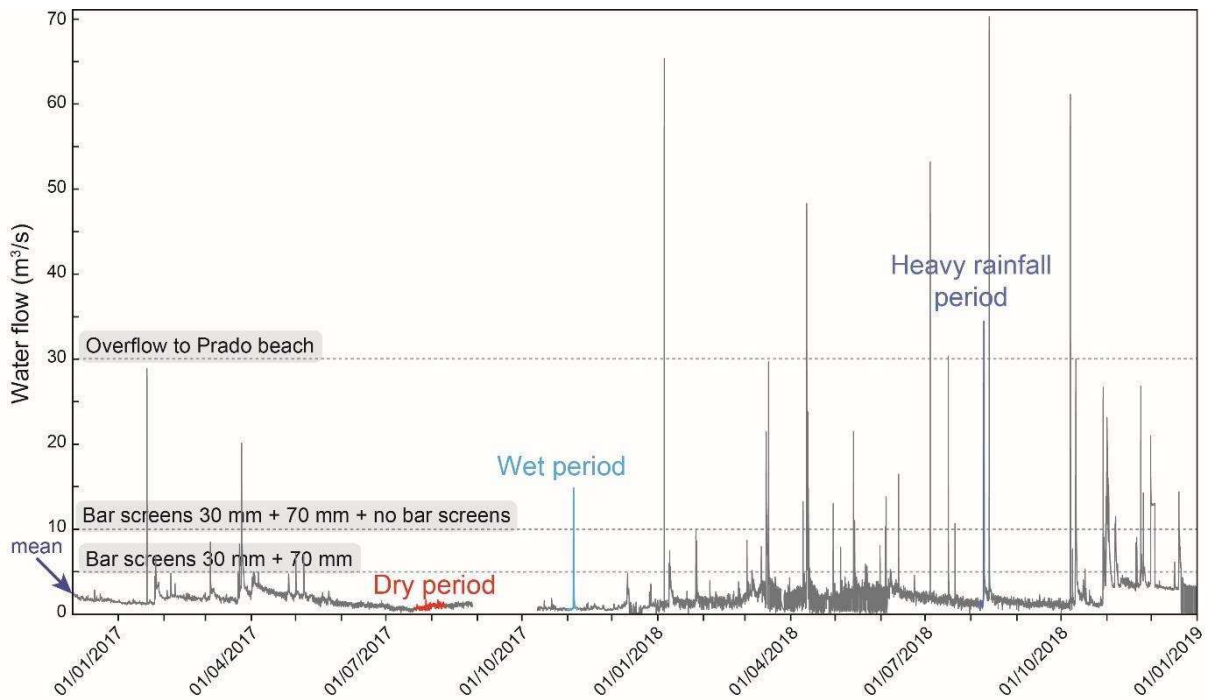
159 In total, three samples were analyzed during dry, wet and heavy rainfall periods
160 determined close to Pugette station according to the occurrence and magnitude of maximum
161 precipitation recorded at Valentine, St Cyr and Pugette stations (**Figure 1B**). Precipitation
162 patterns in this small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

165 July and the 9th August 2017 with a mean water flow at Pugette of $0.9 \pm 0.3 \text{ m}^3/\text{s}$. During this
166 period, all the water volume was bar screened at 3 cm.

167 The designated “wet period” corresponded to 7 days during autumn between the 1st
168 November and the 7th of November 2017 with a single rainfall event occurring the 5th of
169 November. Cumulated precipitation was 49.2 mm with a peak water flow of $14.8 \text{ m}^3/\text{s}$ and a
170 mean water flow of $1.3 \pm 2.5 \text{ m}^3/\text{s}$ over the whole period. During the surveyed “rainfall event”,
171 the water flow was on average of $14.0 \text{ m}^3/\text{s}$ for at least 3 hours, meaning $43,200 \text{ m}^3$ were not
172 bar screened at all and $54,000 \text{ m}^3$ were bar screened at 7 cm, which is respectively 28.5% and
173 35.7% of the total volume at that time. The remaining 35.8% were thus bar screened at 3 cm.

174 The designated “heavy rainfall period” corresponded to 3 days during summer between
175 the 7th of August and the 9th of August 2018, but the surveyed “heavy rainfall event” occurred
176 the 9th of August. Cumulated precipitation was 76.6 mm with a mean water flow of 4.5 ± 7.9
177 m^3/s and a short duration peak to $34.4 \text{ m}^3/\text{s}$ (~1h) over the whole period. During the heavy
178 rainfall event, the water flow was on average of $23.0 \text{ m}^3/\text{s}$ for at least 9 hours, meaning $421,200$
179 m^3 were not bar screened at all — in which $15,840 \text{ m}^3$ overflowed to the Prado beach — and
180 $162,000 \text{ m}^3$ were bar screened at 7 cm, which is respectively 56.5% and 21.7% of the total
181 volume at that time. The remaining 21.8% were thus bar screened at 3 cm. So, less than the
182 half of the water volume has been bar screened.

183



184

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

188

189 **2.3. Sampling procedure**

190 Grab sampling were performed in Pugette station where organic and anthropogenic debris
 191 are automatically screened and transferred into dumpsters, which are big waste containers in
 192 metal with a volume ranging from 19 to 28 m³ (**Table 1**). For the purpose of this ad-hoc study,
 193 dumpsters were emptied when they were completely full for sampling, whereas their content
 194 are usually sent to landfills. So the volume of waste in dumpsters was equal to the volume
 195 capacity of dumpsters. Sampling was performed once by SERAMM and the NGO MerTerre
 196 after each dry, wet, and heavy rainfall period to quantify organic *versus* anthropogenic litter in
 197 volume and to determine the composition of anthropogenic litter by count. Each sample
 198 corresponds to one full dumpster, filled by material coming from both 3 cm and 7 cm bar
 199 screens. Complete filling of dumpsters took 21, 7 and 3 days for dry, wet and heavy rainfall
 200 periods, respectively. The sampling procedure is described and illustrated in **Figure 3**.

201



202

203 **Figure 3:** Sampling procedure.

204

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

219

220 **Table 1.** Sampling strategy of the screened materials in The Huveaune River
 221 (Pugette station). *The accumulation time corresponds to the time needed to
 222 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 Dumpster (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

223

224 **2.4. Waste quantities and mass flow of plastics**

225 For each of the three samples, the number of litter items was extrapolated to the volume of
 226 the corresponding dumpster and hydrological period to get a number of items accumulated per
 227 day for each dry, wet and heavy rainfall period (see **“Litter load” in sup. Data**). Except during
 228 rainfall episodes, most of water is bar screened. Thus, the litter items accumulated in dumpsters
 229 roughly corresponds to the litter items transiting in the river. However, an unknown fraction of
 230 litter is not bar screened for wet periods with a water flow above 10 m³/s, leading to
 231 underestimations. It is then assumed that the concentration of litter in water that is not bar
 232 screened is equal to the concentration of litter in water (items/m³) that is bar screened at the
 233 same time.

234 Only mass flow of macroplastics was calculated, because number to mass ratios are
 235 more reported for macroplastics in literature dealing with riverine litter than for other type of
 236 waste (van Emmerik et al., 2018; Schöneich-Argent et al., 2020; Vriend et al., 2020). The mass
 237 flows of macroplastics M_p (kg/d) for each hydrological period p_i were calculated using
 238 equation 1, with the estimated number of plastic debris N accumulated per day extrapolated to
 239 t time and converted to mass by a mass/number ratio m_p . Plastic debris include item categories

240 from G1 to G124 according to the OSPAR/TSG-ML classifications. The number of plastic
241 debris was converted into mass using a realistic number to mass ratio based on the mass
242 distribution of thousands of macroplastics found in 3 German rivers, i.e median value of 1.0
243 g/macroplastic as the min value and 5.3 g/macroplastic on average as the max value
244 (Schöneich-Argent et al., 2020, 2021). This interval seems reasonable, because the mean mass
245 per plastic debris was 3.2 g in the highly polluted Saïgon River in Vietnam Van Emmerik et
246 al., 2018), whereas this mass was 5.4 g in the far less polluted Rhine River (Vriend et al., 2020).
247

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

248
249
250 The $M_P(x)$ was extrapolated to a year and weighed relative to the mean fraction of time
251 corresponding to dry, wet and heavy rainfall periods to get a mean annual mass flow of plastic
252 debris. Then, macroplastic emission into the sea was estimated based on the volume of water
253 overflowed toward the Prado beach (monitored by SERAMM), i.e., into the Sea and its plastic
254 mass concentration, and its mass concentration in macroplastic (See **“Water flow” in sup**
255 **data**). This estimate is conservative, because litter potentially passing through bar screens or
256 not screened (for $10 < \text{water flow} \leq 30 \text{ m}^3/\text{s}$) and finally reaching the sea is not quantifiable by
257 nature. Thus, corresponding mass flows of macroplastics were only reported to the water
258 volume, which has been bar screened (See **“Water flow” in sup data**). Finally, macroplastic
259 mass flows were normalized to the basin population to enable reliable comparisons through
260 spatial scales.

261

262 3. Results and discussion

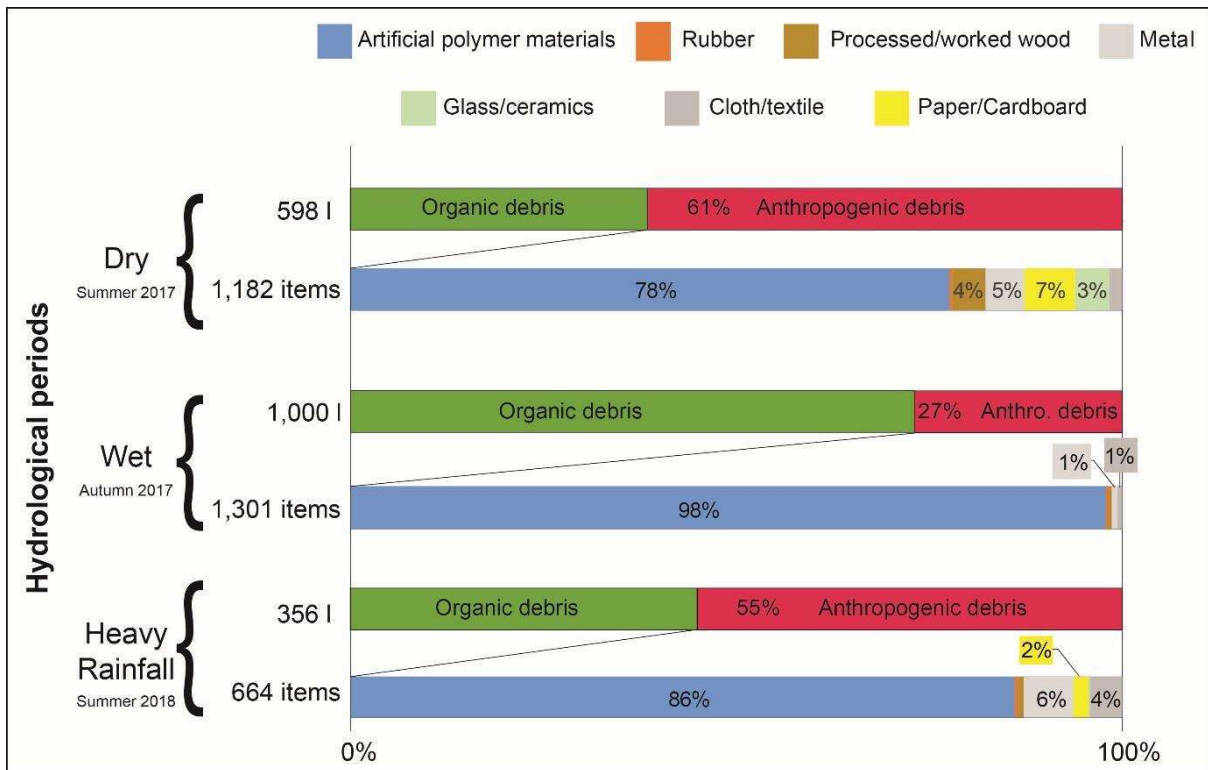
263 3.1. Composition of the screened materials

264

265 *Organic debris versus anthropogenic debris*

266 Bar screens settled on the full width of the Huveaune River captured large volume of
267 debris, i.e. 0.9 to 9.3 m³/d (**Table 1**). Organic debris in screened materials are a major fraction
268 in volume relative to the total volume of debris (**Figure 4**). The highest fraction of organic
269 debris is recorded during wet periods corresponding to 73% of the total volume. In contrast,
270 the dry period recorded in The Huveaune River shows the highest fraction of anthropogenic
271 materials, i.e. 61%. The heavy rainfall event recorded in The Huveaune River shows
272 intermediate level of anthropogenic waste (55%) and organic debris (45%). The fraction of
273 organic debris is greater during the wet period than during the dry and heavy rainfall periods
274 most probably because the two latter were sampled during summer, whereas the wet period
275 correspond to the autumn season where trees are losing their leaves. Treilles et al. (2021) also
276 reported more organic material during autumn than during the rest of the year in screened
277 material of runoff water in a peri-urban area. In any case, organic debris may enhance transport
278 of plastic debris as demonstrated in Vietnam where plastic transport correlated with
279 concentrations of water hyacinths (van Emmerik et al., 2019).

280



281

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

285

286 *Type of anthropogenic debris*

287 A total of 3147 litter items were sorted and counted according to OSPAR/TSG-ML
 288 classification (MSFD Technical Subgroup on Marine Litter, 2013) for dry (n =1,182), wet (n=
 289 1,301) and heavy rainfall periods (n=664). All data are reported in **“Screened material” in**
 290 **sup. Data**. Results show that anthropogenic waste is mostly composed of plastic debris (83%
 291 on average) recorded as “artificial polymer materials” (**Figure 4**), in agreement with González-
 292 Fernández et al. (2021) who reported similar results for European rivers with 82% plastic items.
 293 The fraction of plastic debris ranges between 78% during the dry period and 98% during the
 294 wet period. Other types of material correspond to minor fractions with glass/ceramics (0 – 3%),
 295 metal (1 – 6%), paper/cardboard (0 – 7%), processed wood (0 – 4%), cloth/textile (1 – 4%) and
 296 rubber (0 – 1%). Low proportions of those litter types are most likely the result of “washing”

297 by the water that disintegrates paper/cardboard, while metal, glass and textiles may sink. This
298 is supported by higher proportions of those materials (16% glass, 13% paper, 11.5% metal)
299 found on riverbanks in Germany rivers by schoolchildren following a wide citizen sciences
300 program (Kiessling et al., 2019). Littering was mostly attributed to recreational activities,
301 suggesting local sources, rather than remote sources related to riverine transport and subsequent
302 washing/sorting processes.

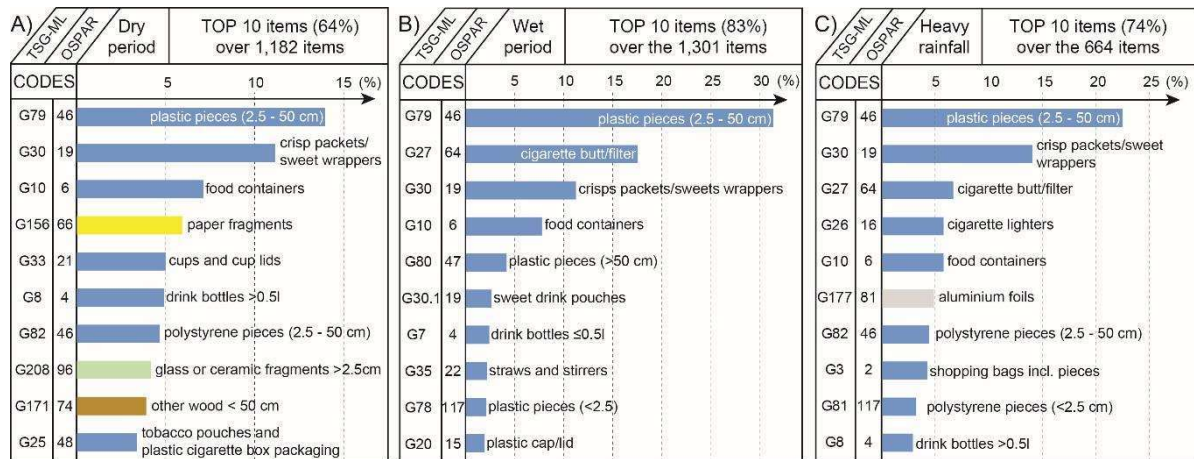
303 Screened anthropogenic debris during the wet period are characterized by a lower
304 diversity in the types of material when compared to the dry period (**Figure 4**). But dumpsters
305 filled up 4 – 6 times faster during the wet period (3.4 m³/d) than during the dry period (0.9
306 m³/d; **Table 1**), suggesting enhanced transport of riverine litter, including different types of
307 material and organic debris. The highest rate of filling corresponds to the heavy rainfall event
308 (9.3 m³/d), which shows an intermediate diversity regarding types of material.

309

310 *Top 10 specific items*

311 The most abundant specific items commonly featuring in the Top 10 of dry (64% of
312 total), wet (83% of total) and heavy rainfall periods (74% of total) are (i) unidentified plastic
313 pieces between 2.5 and 50 cm (G79), (ii) food wrappings with crisps packets/sweet wrappers
314 (G30), and (iii) food containers (G10). Tobacco-related products (G25, G26 or G27) and drink
315 bottles (G7 or G8) are also present in all Top 10 specific items. However, small items able to
316 pass through bar screens (i.e. < 3 cm) such as cigarette butts/filter (G27), plastic pieces < 2.5
317 cm (G78) or polystyrene pieces < 2.5 cm (G81) are only found in Top 10 for wet and heavy
318 rainfall periods (**Figure 5**). This hydrological-related pattern suggests that cigarette butts could
319 be considered as a marker of urban runoff. Alternatively, this pattern may be related to clogging
320 with organic material with higher water flow and enhanced riverine litter transport. This is
321 supported by results obtained in a sub-basin of the greater Paris area where most of the cigarette

322 butts from urban runoff were collected by 1 cm bar screens, despite a previous screening of 6
 323 cm (Treilles et al., 2021). Thus, fast clogging during wet periods may act as narrower bar
 324 screens, whereas small items are not collected during dry periods, when clogging is less likely.
 325



326
 327 **Figure 5:** Top 10 items collected during dry, wet and heavy rainfall periods.

328

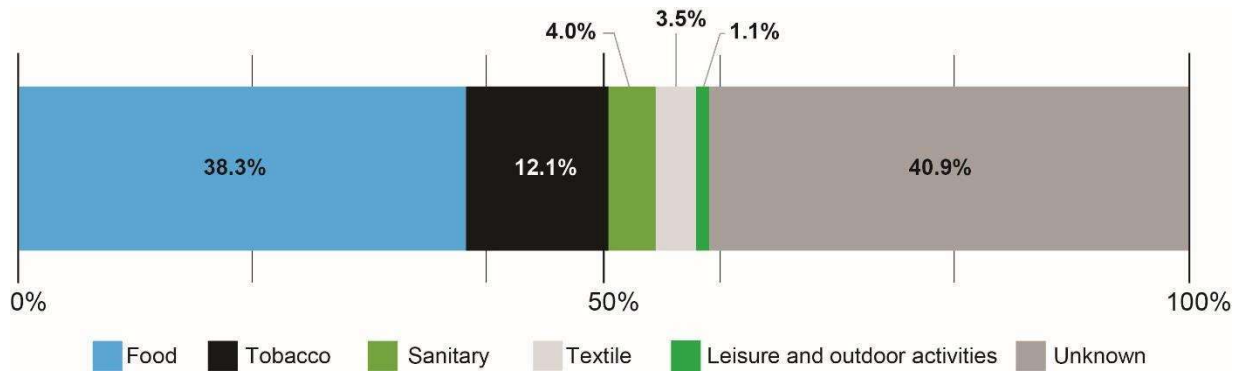
329 Those results are in line with other studies in rivers across Europe showing that
 330 unidentified plastic fragments (2.5–50 cm) and Single Use Plastics (i.e. bags, bottles and other
 331 packaging) are among the most abundant specific items (González-Fernández et al., 2021).
 332 Treilles et al.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

337

338 *Economic sectors*

339 When possible, identified specific items were assigned to their respective economic sectors
 340 (Figure 6; see “Economic sectors” in sup. data). Item counts were extrapolated to the whole
 341 dumpster for each sample (see section 2.3) and aggregated to get a clear overview of the

342 economic sectors they correspond to. It yields 120,879 specific items in which 40.9% were not
343 assigned to an economic sector because they were classified as “fragments” or ambivalent
344 categories. The first identified economic sector is food (38.3%), including all type of food
345 packaging (G7, G8, G10, G20, G24, G30, G33, G150, G151, G159, G175 to G178, G200) and
346 other related accessories like straws, stirrers (G35), lolly sticks (G31), cutlery and trays (G34).
347 The second economic sector is related to tobacco products (12.1%), including cigarette butts
348 and filters (G27), lighters (G26), plastic cigarette box packaging (G25), and cigarette boxes
349 (G152). Then, comes the sanitary sector (4.0%) with a sewage component, which includes wet
350 wipes (G145), cotton bud sticks (G95), sanitary towels (G96), and a hygiene-related component
351 like cosmetic containers (G11) and diverse household products (G29, G39, G98). Other textiles
352 (G135 to G145, including wet wipes) and leisure and outdoor activities (G32, G90, G125 and
353 G126) correspond to 3.5% and 1.1% of all specific items, respectively. Most food and tobacco
354 products are related to packaging, which roughly corresponds to 50% of the specific items.
355 Those results are in line with data compiled by Schwarz et al.(2019), showing packaging-
356 related products represent up to 75% of the items in rivers followed by household products
357 (2.5%), which may roughly correspond to sanitary, household and leisure and outdoor activities
358 in our study. Comparisons remain difficult because there is no clear correspondence in
359 literature between a specific item category and an economic sector. This may be solve in future
360 by the recently updated and harmonized Joint List of categories at the European scale that
361 unambiguously reports corresponding sources and economic sector for each specific item
362 category (<https://mcc.jrc.ec.europa.eu/main/dev.py?N=41&O=459>).



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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

384 focused on changing behavior of the concerned people as suggested by Ryan et al. (2020) who
385 note even a national ban on tobacco sales during the pandemic of Covid-19 did not result in
386 decrease of cigarette butts in urban streets of Durban, South Africa: 33% litter were tobacco-
387 related products by counts over there at that time.

388

389 **3.2. Quantitative assessment**

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

398 When considering all categories of litter items, 1,782 litter items/day (1,383 plastics/day)
399 flew in the Huveaune River during the dry period, 4,461 litter items/day (4,367 plastics/day)
400 during the wet periods and 17,408 litter items/day (14,971 plastics/day) during the heavy
401 rainfall episode. These results are equivalent to 74 litter items/h (dry period) to 725 items/h
402 (heavy rainfall episode) and fall into the upper range of the floating litter fluxes estimated for
403 the 17 rivers ranging into the small to medium basin category (100–10,000 km²) reported by
404 González-Fernández et al. (2021). Small and mountainous Chilean rivers also show relatively
405 low floating litter flow, when compared to the Huveaune River, with 10.1 litter items/h
406 (Honorato-Zimmer et al., 2021). This is probably the result of underestimation of litter by
407 visual counting, especially during extreme events that are often missing in the literature. In
408 contrast, our methodology considers the whole water column and extreme events.

409 Nevertheless, according to van Calcar and van Emmerik (2019) who reported visual counting
410 of floating plastic items only, the Huveaune River falls into the range of the Seine River
411 corresponding to the upper range of European rivers and lower range of Asian rivers, roughly
412 2,000–20,000 items/d.

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

433 This approach, which in turn considers mass flows of plastic debris as a function of dry,
434 wet and heavy rainfall periods, also enables to estimate the relative contribution of each
435 hydrological period in the total annual mass flow. So, 63.3% of the total mass flow of
436 macroplastic debris may occur during dry periods, 25.3% during wet periods and 11.4% during
437 heavy rainfall episodes. Thus, wet periods and even more heavy rainfall episodes contribute to
438 the mass flow much more than dry periods relative to their respective timespan, i.e. 87.5%,
439 11.1% and 1.5% of the year for dry, wet and heavy rainfall periods, respectively. Those findings
440 support the fact that macroplastic transport exhibits a strong seasonality (van Emmerik et al.,
441 2019). Beyond clear seasonality, our study shows the impact of a single rainfall event with
442 flash flood events probably being major drivers of the plastic transport as suggested by models
443 in more affected regions of the world along with the ongoing global warming (Roebroek et al.,
444 2020). Similar conclusions were drawn in Chile at the national level from their fast flowing
445 mountain rivers that may rapidly flush litter downstream with important fragmentation during
446 transport, especially during high water discharge (Honorato-Zimmer et al., 2021).

447

448 **3.3. How much plastics finally reach the sea?**

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

458 debris depending on their size. However, it does not provide direct evidences on the plastic
459 leakage into the sea.

460 In this paper, we propose a way to estimate the plastic emission into the sea based on the
461 volume of water overflowing toward the sea and its mass concentrations in macroplastic. A
462 mean quantity of macroplastics can be estimated for each hydrological periods of measurement
463 relative to the volume of water, which is bar screened (either at 3 cm or 7 cm), leading to a
464 mass concentration of macroplastics in water. It yields 17 – 86 mg/m³ for the dry period, 46 –
465 232 mg/m³ for the wet period and 65 – 324 mg/m³ for the heavy rainfall period (see **”Litter
466 load” in sup data**). The latter concentration is applied to the volume of water bypassed toward
467 the Prado Beach and the Sea, i.e 6.2 10⁶ m³/yr on average over 2018/2019 (see **”Water flow”
468 in sup data**). It yields 0.4 – 2.0 mt/yr, which is equivalent to 0.8 – 3.9 g/cap/yr of macroplastic
469 debris entering the Sea through the Huveaune River. It can be considered that almost all this
470 quantity will reach the sea instantaneously after overflow, because the channel between Pugette
471 and the Prado Beach is only 2 km long, straight and water flow during those episodes are at
472 least 10 times higher than the average water flow. Also, there are no tides able to push debris
473 back on lands (e.g. Tramoy et al., 2020b). This estimate is on average two times higher than
474 the modelled estimate of González-Fernández et al. (2021) that yield between 41,719 and
475 247,961 items (lowest and highest values), in which 82% of them were plastics, i.e. 0.05 and
476 1.3 mt/yr (for 1.0 to 5.3 g/macroplastic). Although in the same order of magnitude, this model
477 may yield more conservative estimates than ours because it only considers floating
478 macroplastics and avoids extreme events. The estimate of 0.4 – 2.0 mt/yr of macroplastics
479 reaching the Sea through the Huveaune River should be added to the previous mass flow
480 estimated in the bar screens, because it corresponds to the “unseen” plastic mass that is not
481 captured by bar screens. Finally, the total mass flow of plastic debris transiting in the Huveaune

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

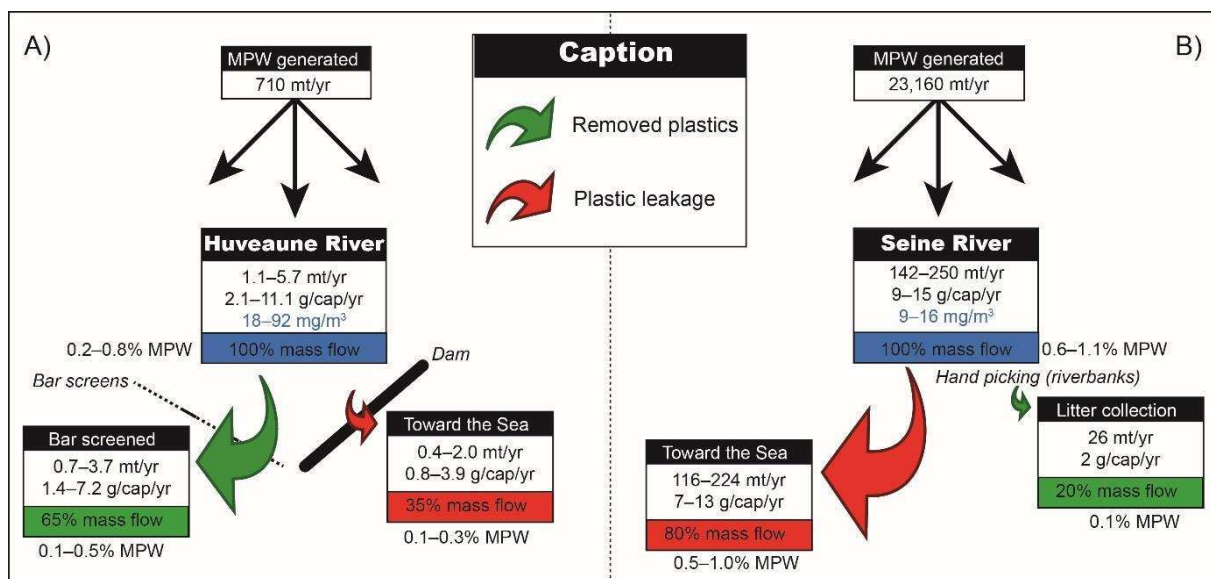
484

485 **3.4. From global models to local field studies**

486 Local field studies are used to calibrate and validate global models (e.g. Lebreton et al.,
487 2017; Schmidt et al., 2017; González-Fernández et al., 2021; Meijer et al., 2021). Those field
488 studies must use the same methodology. They are often based visual counting for
489 macroplastics. The use of alternative holistic approaches based on ground-truth data like in this
490 work for plastic flux estimations does not help to better calibrate global models, but come
491 challenging their validity and questioning their results. Figure 7 shows a synthetic comparison
492 between macroplastic mass flows estimated in the Huveaune River (**Figure 7A**) and in the
493 Seine River (**Figure 7B**), which is based on another holistic approach (Tramoy et al., 2021).
494 Mismanaged Plastic Waste (MPW) are also represented and were estimated according to
495 Jambeck et al. (2015) to enable comparisons with other studies using MPW as an indicator.
496 Annual plastic emissions into the sea correspond to 0.1–0.3% of the total MPW generated in
497 the Huveaune watershed and 0.5–1.0% in the Seine watershed (**Figure 7**; Tramoy et al., 2021).
498 As noticed and discussed for the Seine River, but also for other European rivers,
499 Jambeck's approach (MPW indicator) overestimates the input of plastics into rivers and into the
500 Ocean by one to two orders of magnitude and/or the vast majority of plastic debris are removed
501 before reaching the sea or accumulate on lands and river banks (e.g. Castro-Jiménez et al.,
502 2019; Schöneich-Argent et al., 2020; Vriend et al., 2020; Tramoy et al., 2021). Refining global
503 models of plastic export as recently proposed by Meijer et al. (2021) is required. These authors
504 refined global annual emissions of plastics (excluding microplastics) with estimates ranging
505 between 0.8 million and 2.7 million metric tons per year. For France, they estimated 0.85%
506 MPW were emitted into the Ocean through rivers, not too different from what we found in the

507 Huveaune River or in the Seine River. Most importantly, they shed new lights on the relative
 508 contribution of huge and small rivers showing that small urban rivers, especially in South East
 509 Asia, were the most contributing rivers to the worldwide plastic pollution. The model
 510 developed by González-Fernández et al. (2021) came to the same conclusions for small coastal
 511 basins (<100 km²) in Europe, suggesting that small basins are more efficient in transporting
 512 litter to the sea than large rivers.

513



514

515 **Figure 7:** Synthesis of the macroplastic mass flows in the Huveaune River (A) and the Seine River (B). Data from
 516 the Seine River are based on Tramoy et al. (2021). MPW calculations are recalculated based on Jambeck et al.
 517 (2015) with a MPW generation in France of 0.0038 kg/cap/d (1,387 g/cap/yr), 512,000 inhabitants in the
 518 Huveaune watershed and 16,700,000 in the Seine watershed.

519

520 When mass flows of plastic debris estimated in the Huveaune River or in the Seine
 521 River are normalized to the population of the watershed, results converge to a similar order of
 522 magnitude of 10 g/cap/yr (**Figure 7**). It decreases to ~1 g/cap/yr for the Huveaune River when
 523 only plastic emissions into the sea are considered. At the European scale, annual plastic
 524 emissions of floating macroplastics are in the range 1–10 g/cap/yr (González-Fernández et al.,
 525 2021). Those authors found roughly 1,500–5,000 mt/yr of macroplastics are entering into the

526 seas through >30,000 rivers (including small basins <100 km²), which is equivalent to 2–7
527 g/cap/yr for 694 million inhabitants in Europe included in their mean-based estimate. Notice
528 that strong heterogeneities exist within Europe with for example German rivers showing plastic
529 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
530 Weser River, and 0.06 and 16.1 g/cap/yr in the Elbe River, even though estimates also included
531 plastic debris on riverbanks, riverbed and water column (Schöneich-Argent et al., 2020, 2021;
532 see "**Lit. data**" in sup. data).

533 At the basin scale, the main difference between the Huveaune River and the Seine River
534 lies in the respective fraction of litter collected and returned to the waste management system,
535 i.e. 65% of the annual macroplastic mass flow is removed by bar screens, whereas this fraction
536 falls to 20% in the Seine River with hand collection of litter on estuarine riverbanks. However,
537 the anthropogenic pressure normalized to the surface of the Huveaune watershed
538 (~1,100 cap/km²) is much stronger than in the Seine watershed (~200 cap/km²), with a much
539 lower dilution effect in the Huveaune River (~2 m³/s), than in the Seine River (~500 m³/s).
540 This makes the plastic pollution much more visible for local residents in the Huveaune River
541 than in the Seine River. Then, there is a citizen demand to “solve” this visual disorder of
542 riverine litter. Redirecting polluted water with grey infrastructures, such as giant bar screens at
543 Pugette station for better waste management, partly respond to this demand (communication
544 by SERAMM, <https://madeinmarseille.net/52854-seramm-dernier-kilometre-huveaune/>).

545 This task becomes almost impossible during heavy rainfall and storm events. Despite their
546 relative efficiency for collecting riverine litter most of the time, grey infrastructures like giant
547 bar screens are not trivial. It requires anthropizing an entire section of river with many cubic
548 meters of concretes, thus sacrificing ecological continuity. In addition, this does not solve (i)
549 the upstream dissemination of riverine litter and thus the induced visible pollution for residents,
550 (ii) the transport of smaller plastic debris than the bar screens spacing, or (iii) flash flood-related

551 riverine litter which is bypassed to the sea. In addition, 585 ± 138 mt/yr of riverine litter, on
552 average, are dumped from bar screens in Pugette and from the other similar structure settled on
553 the Aygalades, a tiny waterway North of Marseille (SERAMM, pers. Com.). This means that
554 hundreds metric tons of organic litter that was supposed to be flushed into the sea – probably
555 supporting marine life and natural ecosystem cycles – are removed to remove few metric tons
556 of plastic debris each year. Separating organic litter for composting and anthropogenic litter
557 for recycling is furthermore not economically valuable, so all litter is locally dumped into
558 landfills. This extreme anthropization and its consequences finally raises questions about
559 "sustainable" development policies in urban areas and our society's relationship with nature
560 (e.g. Rowiński et al., 2018). This question is beyond environmental cost/benefit analysis, even
561 though other parameters than riverine litter are sometimes considered such as: biodiversity,
562 ecological continuity, flood risk, river ecosystem services or river transport activities.

563

564 **4. Concluding remarks**

565 A grey infrastructure is settled at Pugette on the Huveaune River, a small urban river in
566 Marseille, South of France, for redirecting water through bar screens and a pipe to prevent litter
567 occurrence on the highly frequented Prado beach, 2 km westward. Opportunistic grab sampling
568 together with high frequency monitoring of water flow from the structure manager SERAMM
569 enabled to characterize riverine litter polluting the river and eventually reaching the Sea.
570 Plastics referred to as artificial polymer in the OSPAR/TSG-ML classification corresponded to
571 83% (by count) of the total riverine litter. The main categories previously reported in European
572 rivers are fragments and single-use items (e.g. bottles, food wrappers and packaging, bags) and
573 the Huveaune River is no exception. Tobacco-related single-use products are also abundantly
574 represented in our data in contrast to data coming from visual counting, probably because
575 cigarette butts – which are dominant in stormwaters – are invisible to observers and/or already

576 fragmented into fibers, or sunk below the water surface. Notice that economic sectors and litter
577 sources will be unambiguously reported in future works with the recently updated and
578 harmonized Joint List of categories at the European scale
579 (<https://mcc.jrc.ec.europa.eu/main/dev.py?N=41&O=459>).

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

590 The Huveaune River is a typical study case showing a non-negligible and uncontrolled
591 leakage of riverine litter remains, despite all recovery systems implemented in well-developed
592 countries like in France. As suggested by González-Fernández et al. (2021), this supports
593 prevention policies rather than end-of-pipe solutions and production/use regulations on a global
594 scale as well as economic-social innovations focused on changes in consumption habits and
595 behaviors. Most recently, UN made similar recommendations for tackling marine litter on a
596 global scale with a systemic approach including (i) the need to translate words into actions, (ii)
597 more regulations at national scales and coordination on a global scale, (iii) immediate
598 implementation of a circular plastic economy (e.g. reduce, reuse, repair, replace, recycle), (iv)
599 better regulation and transparency of the international trade in plastic waste to protect people
600 and nature with the Basel Convention as an important initial step, and (v) developing better

601 and more harmonized monitoring strategies that are capable to evaluate the impact of marine
602 litter policies (UN Environment Programme, 2021). The last recommendation should be
603 achieved by implementing monitoring in routine use in different environmental compartments
604 from sources (i.e., urban areas) to receiving environments (i.e. rivers and ocean), with common
605 baselines like the OSPAR/TSG-ML classification and its updates. The use of existing
606 infrastructures like the bar screens in the Huveaune River should then be considered as
607 monitoring tools.

608

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610

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614

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