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Litter in French urban areas - Part 2: transport dynamic and fluxes in stormwater.

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Abstract

Urban areas constitute a major hotspot of litter, including plastic litter, that stormwater can wash off towards waterways. However, few studies quantified and characterized litter densities in urban areas and fluxes transported by stormwater networks. Moreover, little information is available on litter transport dynamics in stormwater, and on the factors driving this transport. This study aims at characterizing and quantifying litter amounts transported by stormwater of two nested French urban catchments (total surface area of 105 ha). Litter densities relative to land uses and rain events were investigated in the same catchments as in a companion paper (Ledieu et al., 2024). The present study explores the impact of rain events on the transport of urban litter in stormwater. Litter collection and characterization combined with a capture/recapture experiment using tagged litter placed in stormwater inlets show total litter fluxes of 29 kg/yr, in which 14 kg/yr are plastics, exported at the stormwater outlet. These fluxes confirm that stormwater runoff is a considerable pathway from urban surfaces to

27 waterways, especially regarding small plastic litter (< 2.5 cm). Item transport dynamic is however not
28 linear and only 0.3% of the urban litter appear remobilized. Litter transport dynamics depends on several
29 factors (urban litter densities, hydrometeorological parameters, item composition and morphologies, and
30 stormwater management systems) that should be considered in global models.

31

32 **Keywords**

33 Plastic litter, litter sources, rain events, stormwater network, mitigation strategies

34

35 **1. Introduction**

36 By concentrating the human population and activities, high amounts of waste are generated in urban
37 areas. In these areas, waste is managed by collection/cleaning services, or littered (deliberately or
38 accidentally), often depending on the economic development of countries (Hoornweg and Bhada-Tata
39 2012). Although waste management systems are becoming increasingly efficient in European countries,
40 the population growth and consumer society lead to an explosion in waste production, particularly
41 plastic waste (Heinrich Böll Stiftung et al. 2020; Karimi and Faghri 2021). Littered items can either be
42 reintroduced in the waste management system by municipal services, or stay accumulated on urban
43 surfaces and potentially accumulate in soils, or be transferred towards waterways and subsequently to
44 the sea. Several transfer pathways have been identified in urban areas: domestic wastewater, urban
45 stormwater and combined sewer overflows (Basilico et al. 2020). Urban water networks are thus
46 suspected of being a major source of litter for waterways, particularly plastic litter (Cesarini et al. 2023;
47 Tasseron et al. 2023). However, little is known about plastic transport by stormwater, and no exhaustive
48 and consolidated data are available on the contribution of stormwater discharges to the riverine plastic
49 pollution.

50 Stormwater can be managed either by combined or by separate sewer systems. These systems, if any,
51 may differ between countries, between cities and even within cities. Combined sewer systems are

52 traditionally used worldwide, but separate sewer systems are used preferably in developed countries
53 since the second half of the 20th century (De Feo et al. 2014) to achieve the reduction of sanitation impact
54 on waterways. In addition, stormwater volumes tend to increase with more intense rain events and
55 increasing urbanization with impervious surfaces that favors runoff. In France and in several European
56 cities, combined sewage networks are mainly present in city centers and separate sewage networks in
57 peripheral areas, that have been urbanized more recently (Rognard and Finck 2020). This makes it more
58 difficult to distinguish the contributions from different sources and transfer pathways (Basilico et al.
59 2020). Besides, current regulations do not impose any specific monitoring of litter discharges in
60 combined sewer overflows (Rognard and Finck 2020). Moreover, these inputs occur during extreme
61 weather events, making them even more difficult to monitor.

62 Some stormwater network infrastructures are designed to limit the entry and the transfer of litter in
63 sewers and to waterways with grates, underflow baffles, hydrodynamic separators (Rognard and Finck
64 2020; Bruttin et al. 2021) or nets. In recent years, with the growing interest in plastic pollution, such
65 structures are sometimes used to specifically monitor litter inputs from urban runoff (e.g. in Tramoy et
66 al., 2022a, b; Martinez and Griffiths, 2023). Nevertheless, most networks are not equipped with retention
67 devices and litter may be directly exported towards waterways (Basilico et al. 2020), with stormwater
68 outlets becoming a point source of litter. Hydrometeorological parameters (e.g. rainfall intensities and
69 discharge volumes) play a key role in the transfer of litter (Treilles et al. 2021; Malik et al. 2021) but
70 this relationship remains poorly understood (Tramoy et al. 2022b).

71 Many models use levels of mismanaged waste on land to estimate the riverine plastic export into the sea
72 (e.g. Jambeck et al., 2015; Lebreton et al., 2017; Schmidt et al., 2017), but the estimation of urban runoff
73 contribution needs to be completed. Integrating such a parameter should lead to more realistic models
74 but because of low empirical data on litter densities on land, it increases their uncertainty (Roebroek et
75 al. 2022). Previously, we investigated litter composition, origin and accumulation rate on the urban
76 surfaces of two residential and commercial areas located in Nantes (France, see Ledieu et al., 2024).
77 That study has demonstrated that 0.6% of the total amount of waste generated in public places are
78 littered, corresponding to 13 t/yr. Nevertheless, accumulation rates of litter have high spatio-temporal

79 variations. In addition, some items may have long residence times on urban surfaces especially when
80 they accumulate in green spaces. A better understanding of transfer pathways, transport and potential
81 retention factors for litter in urban systems is therefore needed to better constrain global models and
82 develop new mitigation strategies (Tasseron et al. 2020; Meijer et al. 2021; Tramoy et al. 2022b;
83 Roebroek et al. 2022; Sherow et al. 2023).

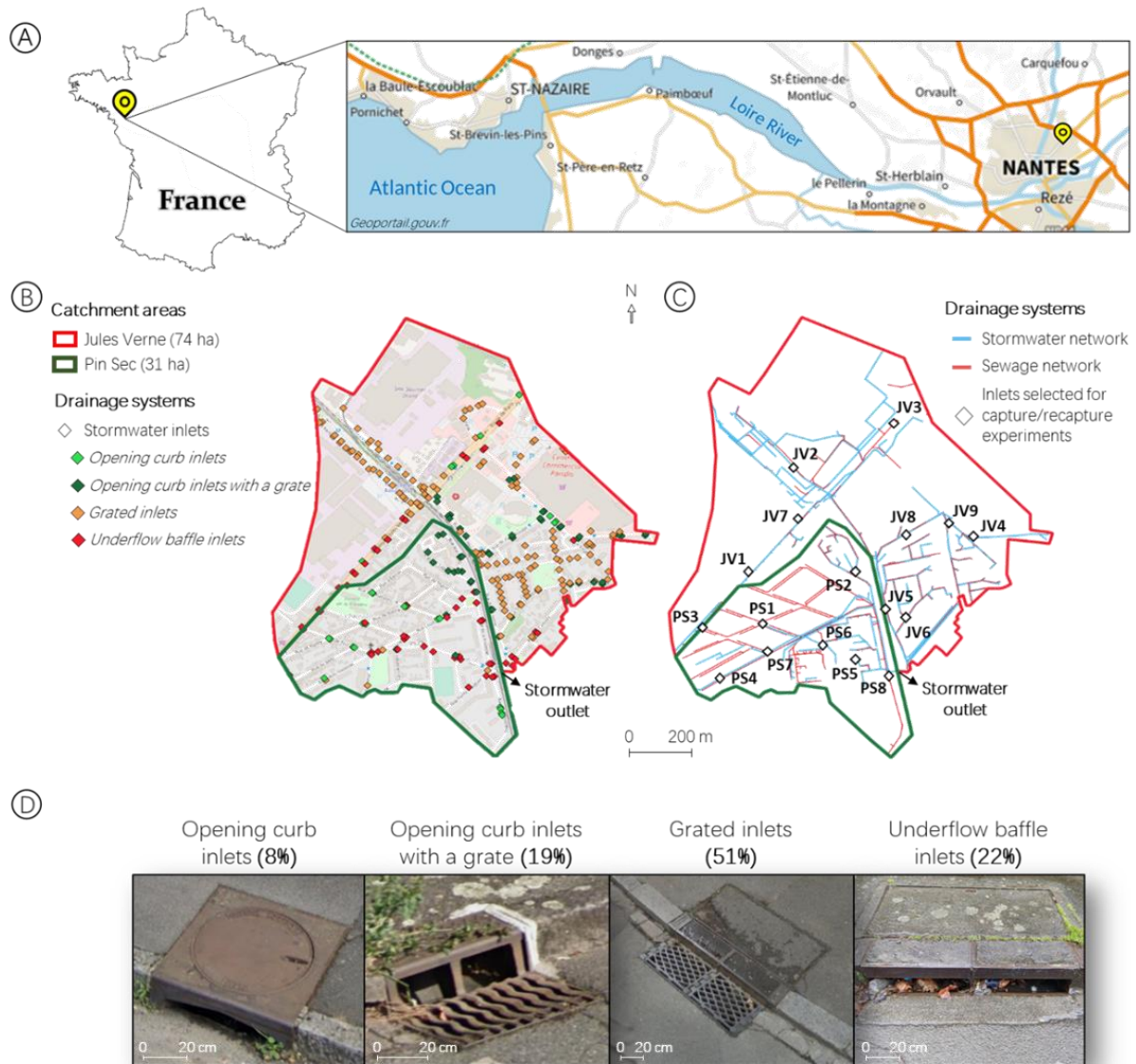
84 The present study aims to (i) characterizing litter composition preferentially transported by urban
85 stormwater, (ii) improving the understanding of litter transport dynamics in stormwater, (iii) quantifying
86 the contribution of stormwater to litter fluxes entering the waterways and (iv) exploring the relationship
87 between litter fluxes and hydrometeorological parameters. Two urban catchments located in Nantes
88 (France) were chosen for this research because their common stormwater outlet is designed as a retention
89 basin allowing the collection of the transported litter. Moreover, litter amount and composition were
90 evaluated on the urban surfaces of these catchments (see Ledieu et al., 2024) and used to compare the
91 typologies and fluxes quantified at the stormwater outlet.

92

93 **2. Materials and methods**

94 2.1. Experimental sites

95 The survey was carried out at two nested urban catchments with gentle slope, located at the north-east
96 of Nantes Metropole (France): Pin Sec (PS) and Jules Verne (JV, Figure 1a). These catchments have a
97 total surface area of 105 ha and include 5,048 inhabitants. Land use is diverse and representative of the
98 general land use of Nantes Metropole. The Pin Sec catchment is mainly residential with individual and
99 collective housing, and the Jules Verne catchment is mainly commercial. The major part of their surfaces
100 is therefore impervious (76 % of impervious surfaces according to a reconstruction of the land use using
101 the buildings from the BD-Topo®, roadways provided by Nantes Metropole Digital Resources
102 Department and the green spaces map from the campaign Fluxsap 2010 (Mestayer et al. 2011)).



103

104 **Fig. 1** A) Location of the studied urban catchments at Nantes agglomeration in France. B) Locations of the stormwater inlets
 105 of the Pin Sec (outlined in dark green) and Jules Verne (outlined in dark red) catchments represented according to their
 106 morphologies (both parameters reported visually using Google Satellite and Google Street View). C) Drainage systems
 107 (stormwater and sewage networks provided by Nantes Métropole) and inlets selected for capture/recapture experiments in
 108 both catchments. D) Photos of the different types of inlets in the Pin Sec and Jules Verne catchments. Their respective
 109 percentages are also indicated

110

111 Stormwater is collected by several inlets with various morphologies (Figure 1b). Most of them are
 112 equipped with structures to limit the transfer of litter to the sewer network i.e. grates (70%) and
 113 underflow baffles (22%; Figure 1b). Photos of each type of inlets are given in the Figure 1d. Stormwater

114 is then transferred through a separate sewer network (total length of 4 km, Rodriguez et al., 2020)
115 towards a common outlet at the south-east of the catchments (Figures 1b and c). This outlet discharges
116 into the perennial Gohards stream. Mainly fed by stormwater runoff, this stream was closed-off in 1945
117 and re-opened in 2012 following a renovation urban planning (Rodriguez et al. 2020). The stormwater
118 outlet was designed in a city park, as a retention basin with an underflow baffle limiting the transfer of
119 litter (Figure S1) to the Gohards stream. Some misconnections between the stormwater and sewage
120 networks exist. The latest conformity survey estimated around 5% of housings misconnected in the Pin
121 Sec catchment, i.e. with wastewater releases in the stormwater network (communication with Nantes
122 Métropole).

123 The investigated area is under an oceanic climate with a mean annual rain amount of 820 mm/yr (1991-
124 2020, Meteo-France station Nantes-Bouguenais; [https://www.data.gouv.fr/fr/datasets/r/6734e889-
125 538e-4feb-9e57-d999a1897433](https://www.data.gouv.fr/fr/datasets/r/6734e889-538e-4feb-9e57-d999a1897433), accessed on 17 January 2024). During the five years preceding this
126 study (2016-2020), the mean discharge in the upstream part of the Gohards stream was 27 L/s (0.4-1,691
127 L/s, min-max). As commonly observed for small urban catchments, the hydrological response is fast
128 (Figure S2; Rodriguez et al., 2020). Overflow of the retention basin is rare, but during this study, two
129 were observed after extreme rain events, in April and August 2022 (Table S1).

130

131 2.2. Litter collection and characterization

132 After an initial cleaning of the retention basin (C0), 18 campaigns (labelled from C1 to C18) of litter
133 collection were carried out between October 2021 and October 2022. Mainly depending on the rain
134 events, integrated periods varied from 5 to 35 days (Table S1) for a total investigation of 335 days. For
135 each campaign, all items above 1 cm were collected on the banks of the retention basin, and in the basin
136 with dip nets.

137 Items were then dried at ambient air and characterized according to the J-list from the MSFD TG-ML
138 classification (Fleet et al., 2021; Table S2). This list classifies items according to their material category
139 (e.g. plastic, metal, paper, ...), type (e.g. bags, bottles, caps, fragments...) and economic sector (e.g.

140 smoking, food-consumption, medical related items, ...). All items were counted and each category of
141 items was weighted. In addition, for smoking and food-consumption related items collected from C1 to
142 C16, brands were recorded when they could be identified.

143

144 2.3. Capture/recapture experiments

145 For a better understanding of litter transport dynamics in the stormwater network and to evaluate the
146 representativeness of litter amounts collected in the basin, two capture/recapture experiments were
147 carried out (a first in April 2022 and a second in November 2022) both with 170 items. Briefly, items
148 collected in the retention basin were tagged with lightweight numbered seals and released in selected
149 stormwater inlets of the catchments. In the Pin Sec and Jules Verne catchments respectively, 8 (labelled
150 from PS1 to PS8) and 9 (labelled from JV1 to JV9) stormwater inlets were selected to represent different
151 morphologies and different distances from the outlet (from 0.1 to 1.3 km of network length, Figure 1c;
152 Table S3). During each experiment, 10 tagged items were placed in each inlet, for a total of 170 items.
153 Then, tagged items have been searched for recovery in the retention basin. If their recovery occurred
154 during a litter collection campaign, these were not included in the litter counts. In case of the retention
155 basin overflows, the downstream part of the Gohards stream was explored. In addition, some parts of
156 the stormwater network (e.g. between JV6 and the retention basin, Figure 1c) were explored by camera
157 to identify litter accumulation zones and/or potential clogging.

158 To test the impact of item morphologies in their transport capacity, experiments were carried out with
159 two types of items. The first experiment was led on 4 April 2022 with bottles (55%) and cans (45%)
160 with various capacity (0.15 to 1.5 L). Every item could actually fit through the openings of the different
161 types of inlets except for grated inlets. Bottles were tested with caps (48%), and without (51%, Table
162 S4). The second experiment was led on 2 November 2022 with sweet wrappers of various types,
163 compositions and capacities but with sizes generally lower than 10 cm. These items were placed in the
164 same 17 stormwater inlets than the for the first experiment.

165

166 2.4. Litter fluxes in stormwater

167 For each campaign, the mass of items and plastic items collected was extrapolated to kg/yr. This was
168 carried out by dividing the collected mass by the number of days integrated, then extrapolated to 365
169 days. This extrapolation was also carried out for the whole period of investigation using the total mass
170 of items collected and the total number of days integrated.

171 For a greater comparability between studies, litter fluxes are often normalized to the number of
172 inhabitants (expressed in g/inhabitant/yr). This enables the fluxes to be compared to the total waste
173 production per inhabitant in Nantes Metropole (i.e. 397 kg/inhabitant/yr considering glass, household
174 and recyclable waste collected door-to-door by municipal services and at the waste collection sites,
175 Nantes Métropole 2022). Litter fluxes are also normalized to the total surface of the catchment area or
176 to the impervious surfaces (expressed in kg/ha/yr) as Treilles et al. (2021) did, considering only
177 impervious surfaces contribute to stormwater runoff.

178 The calculated fluxes may include inputs of items from other sources than stormwater (direct inputs
179 and/or wastewater releases). Such inputs are suspected using the results of characterization but their
180 precise contribution can not be assessed.

181 In addition, the calculated annual fluxes were compared to the annual fluxes of litter estimated on the
182 urban surfaces of these catchments (i.e. 13 t/yr of litter; Ledieu et al., 2024) to evaluate the proportion
183 of items actually removed by stormwater.

184

185 2.5. Hydrometeorological data collection and treatment

186 Rainfall and stormwater discharges are monitored on these catchments since 2006 as part of the Nantes
187 Urban Environment Observatory (ONEVU) and the National Observation Service (SNO) Observil.
188 Rainfall is recorded at a 1 min frequency at 3 rain gauges (3039, Précis Mécanique®) covering the area.
189 Their average values are used for interpretation. Flow discharges at the stormwater outlets from the Pin
190 Sec and Jules Verne catchments are also recorded separately at a 2 min frequency with a Doppler flow
191 meter (2150 Area Velocity Module, Teledyne Isco®).

192 A rain event selection program was used to extract several hydrometeorological parameters for each
193 event: duration of rainy and dry periods, maximum rainfall intensity, maximum flow discharge, and
194 runoff volume (without baseflow). Rain events were considered when the total rain amount exceeds 2
195 mm with a minimum intensity of 1.5 mm/h, and time intervals between two events were 2 h minimum
196 (Berthier 1999). The flood event is considered ended when the runoff volume drained after the rain event
197 is lower than 1/500 of the total runoff volume drained during the rain event, on a 2 min timescale. The
198 baseflow is considered as the flow discharge at the beginning of the rain event and the runoff volume is
199 calculated according to the flow discharge above the baseflow. Total runoff volumes were calculated
200 for each campaign and used to express the litter concentrations in mg/m³.

201 Correlations between the hydrometeorological parameters and amount of items collected (by count and
202 by mass) or item typologies were evaluated using the Spearman correlation coefficient R (Spearman
203 1904) calculated with the package “ggplot2” (Wickham 2016) in RStudio version 2022.7.1.554
204 (RStudio Team, 2022). These correlations were considered as representative and significant if R is equal
205 to or greater than 0.5 and p-values equal to or lower than 0.05.

206

207 **3. Results**

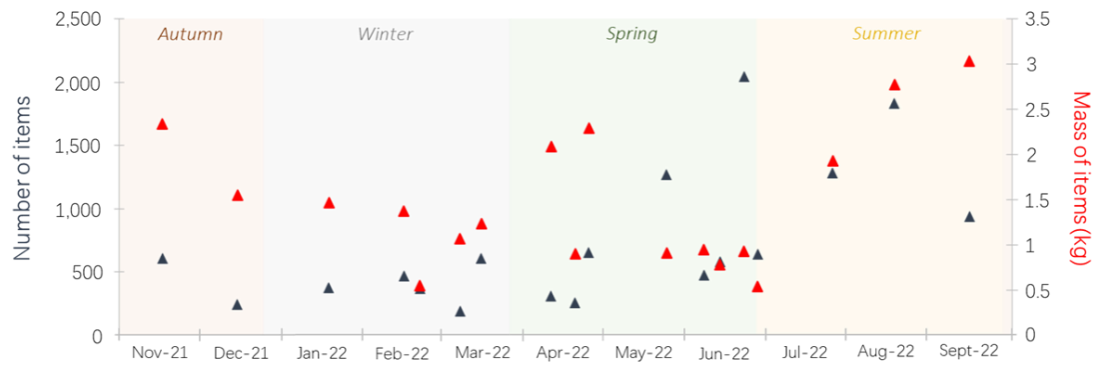
208 **3.1. Litter amount, composition and sources**

209 In total, 13,163 items were collected corresponding to 26.74 kg of litter accumulated during a period of
210 335 days. Per campaign, the number of collected items ranged between 190 (C6) and 2,042 items (C14)
211 and the collected mass between 0.54 (C15) and 3.04 kg (C17, Figure 2a, Table S1).

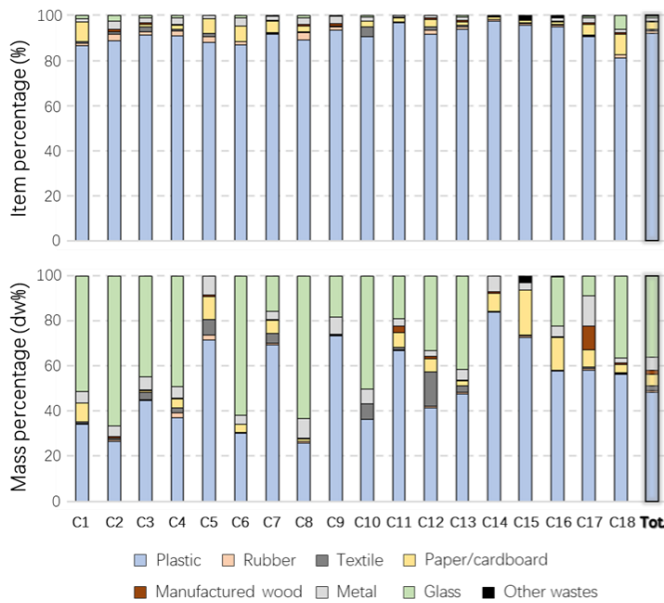
212 The collected items belonged to all categories of materials (i.e. plastic, rubber, paper/cardboard, metal,
213 glass, manufactured wood and textile). By count, plastics were always and largely predominant,
214 representing 92% of the total items. Paper/cardboard ranked second (3%) and metal third (2%). By mass,
215 plastics only represented 48% of the total items, glass represented 36% and metal 6% (Figure 2b).

216

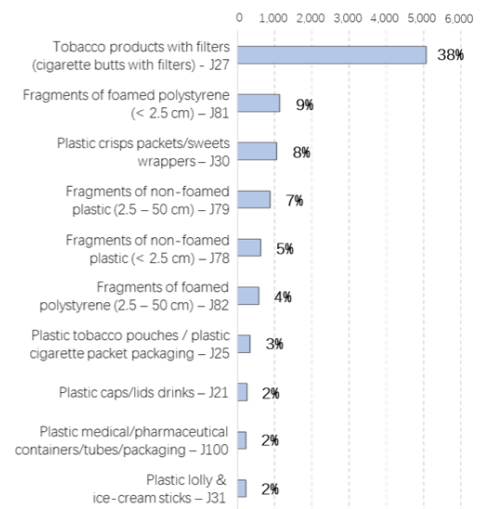
(A) Number and mass of collected items according to the seasons



(B) Categories of materials by count and by mass



(C) Top 10 (by count)



217

218 **Fig. 2 A)** Number (blue triangles) and mass (red triangles) of items collected according to the periods. Seasons are represented.

219 **B)** Percentages of the different categories of materials (by count and by mass) sampled during the 18 campaigns (C1 to C18)

220 carried out for litter characterization and during the total period of sampling (Tot.). **C)** The top 10 type of items by count

221 according to the J-list (Fleet et al., 2021). Percentages of each type of items are indicated

222

223 The collected items belonged to 98 categories over the 201 categories listed in the J-list (Table S2). The

224 10 most abundant type of items represent 80% of the total items by count, and were all plastics. Cigarette

225 butts were the most abundant (J27, 38%), fragments of foamed polystyrene (J81, < 2.5 cm) ranked

226 second (9%) and sweet wrappers ranked third (J30, 8%). The following categories were mostly

227 fragments and containers (Figure 2c). The litter composition was however highly variable according to

228 the campaigns. Only 8 categories were always found in samples: cigarette butts with filters (J27),

229 fragments of foamed polystyrene (< 2.5 cm, J81), plastic crisps packets/sweets wrappers (J30),
230 fragments of non-foamed plastic (0 – 50 cm, J79 and J78), plastic tobacco pouches/plastic cigarette
231 packet packaging (J25), plastic lolly and ice-cream sticks (J31) and metal drink cans (J175, Table S5).

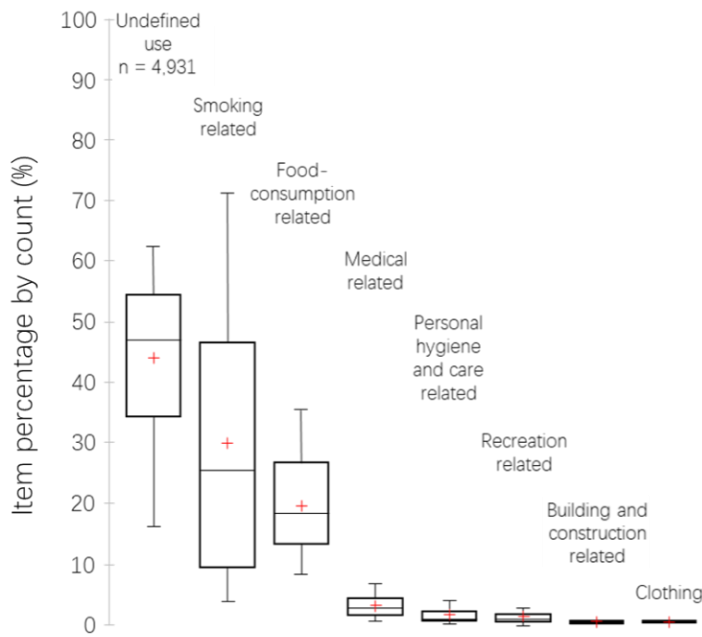
232 Some categories of items may result from direct inputs or wastewater contributions. According to our
233 on-site observations, syringes (J99, n = 49, M = 98 g), medical containers (J100, n = 233, M = 314 g),
234 condoms (J133, n = 21, M = 27 g) and glass bottles (J200, n = 114, M = 9 434 g) may be attributed to
235 specific activities within the park around the retention basin. Moreover, some typical wastewater items
236 like sanitary towels (J96, n = 35, M = 219 g), tampons and applicators (J144, n = 3, M = 6 g), toilet
237 fresheners (J97, n = 2, M = 23 g) and wipes (J237, n = 54, M = 236 g) were observed during some
238 campaigns (Table S5). These items may be attributed to the misconnected houses in the catchments
239 considering that these were virtually not observed on the urban surfaces of the catchments (see Ledieu
240 et al., 2024).

241 The economic sector was identified for 63% of the items by count, belonging to 7 different economic
242 sectors from the J-list. ‘Smoking-related’ (26% by count) and ‘food-consumption related items’ (18%
243 by count) were predominant. ‘Medical’ and ‘personal, hygiene and care related items’ were less present,
244 representing median percentages of 3% and 1% by count, respectively. Items from ‘recreation’,
245 ‘building and construction activities’ as well as ‘clothing’ were also collected but in low proportions (<
246 1% by count, Figure 3a).

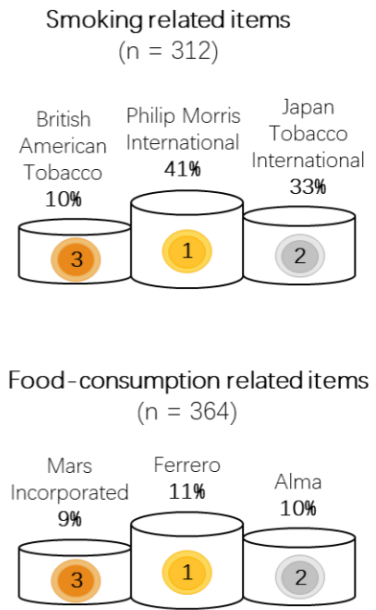
247 Among the smoking related items, the brand of 312 items (7% of the total) could be identified and 35
248 different tobacco brands were recorded. The top 10 brands however represents 87%. Marlboro was
249 predominantly identified, followed by Winston and Camel. The Philip Morris International group
250 therefore lead the top 3 industrial groups in this category (Figure 3b and c).

251 Among food-consumption related items, the brand of 364 items (22% of the total) could be identified
252 and 161 different brands were recorded. The top 10 brands represents 47% with Kinder as leader,
253 followed by Cristaline (water bottle) and Mars. The top 3 industrial groups followed this podium (Figure
254 3b and c).

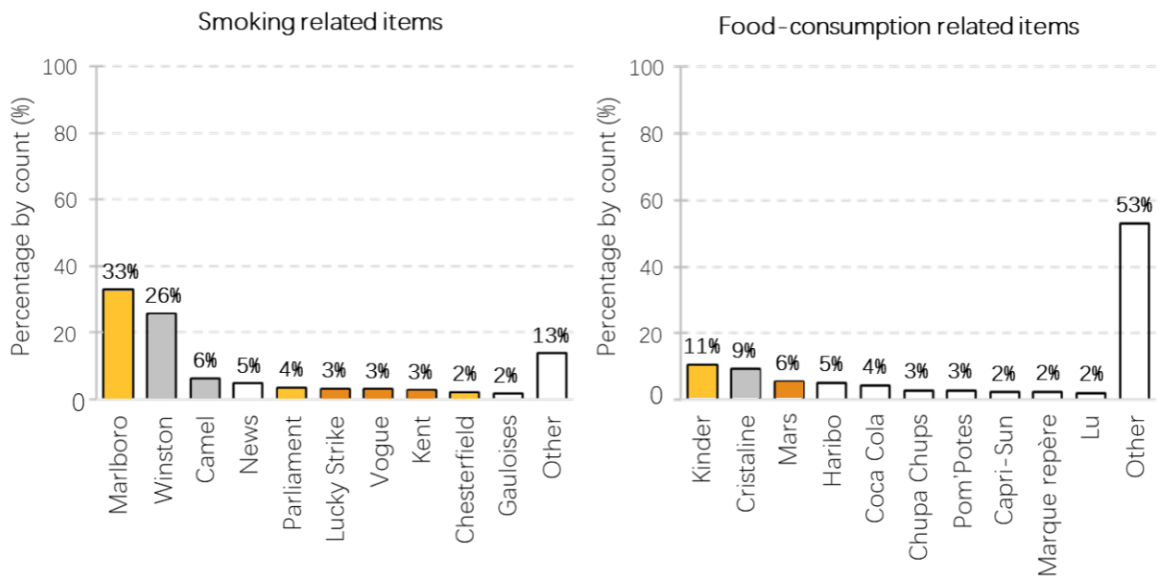
Ⓐ Economic sectors (n = 13,163)



Ⓑ Top 3 groups



Ⓒ Top 10 brands



255

256 **Fig. 3 A)** Boxplots representing the variability (first quartile, third quartile and median; vertical bars: 1.5 times the interquartile
 257 range, red crosses: mean percentages) of item percentages by count according to their economic sectors. B) Top 3 industrial
 258 groups and C) top 10 brands recorded for smoking related and food-consumption related items from C1 to C16. The number
 259 of items for which the brands were identified is indicated. Brands were colored according to the podium of the Top 3 groups.

260

261

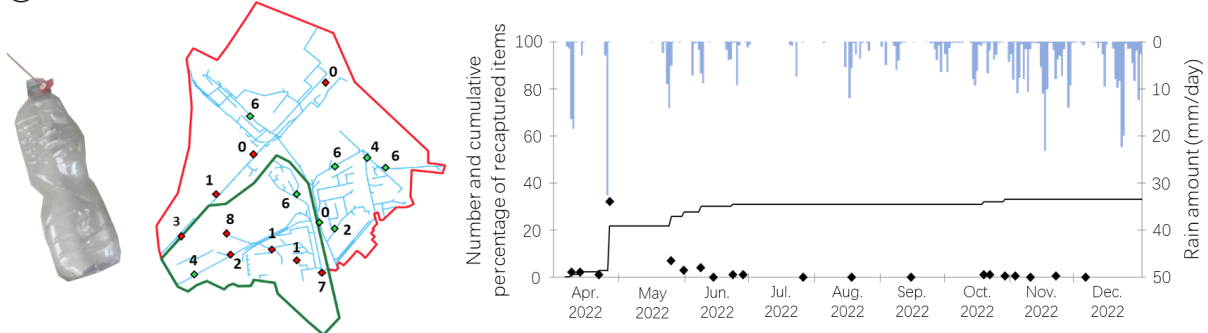
262 3.2. Transport dynamic of the tagged items

263 Among the 340 items used for the capture/recapture experiments, 157 (46%) were recaptured in the
264 basin, 33% of the released bottles/cans and 58% of the released sweet wrappers (Figure 4a and b, Table
265 S3). For bottles/cans, 2 items (1%) were recaptured at the outlet after the first rain event, illustrating a
266 rapid, but low transport by stormwater. The highest number (32 items, 19%) was recaptured 21 days
267 following their release, mostly resulting from an intense rain event (Figure 4a). For sweet wrappers, the
268 highest number (59 items, 35%) was recaptured at the outlet after the first rain event following their
269 release (Figure 4b), illustrating an easier transport of these small items than bottles/cans.

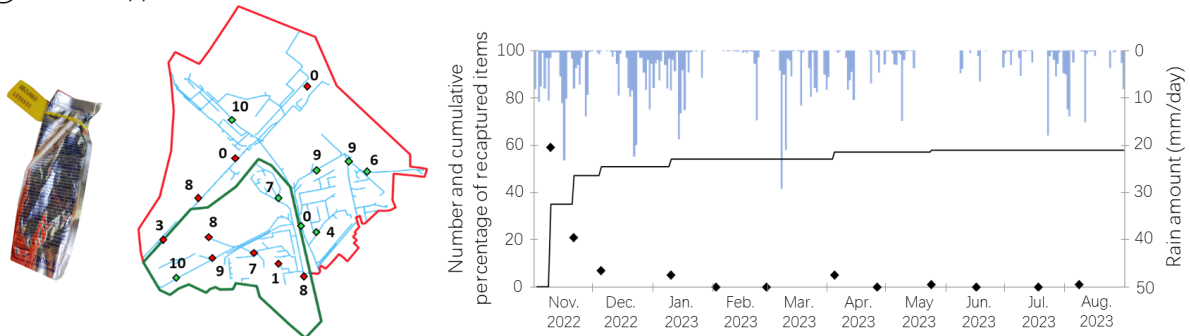
270 Two months after their release, the transport dynamic of bottles/cans became random with 1 item
271 recaptured from time to time regardless of the rain amount (Figure 4a). Three months after their release,
272 a similar dynamic was observed for sweet wrappers (Figure 4b). The last bottle/can and sweet wrapper
273 were recaptured more than seven (231 days) and nine months after their release (279 days), respectively
274 (Figure 4a and b).

275 In addition, more bottles were recaptured (36%) than cans (28%), and most of the recaptured bottles
276 were those with caps (71% of the recaptured bottles, Table S4).

(A) Bottles/cans



(B) Sweet wrappers



277

278 **Fig. 4** Number of tagged items recaptured at each campaign (black diamonds) and cumulative percentages (black line)
 279 according to the daily rain amount for A) bottles/cans (n=170) and B) sweet wrappers (n=170). Maps indicate the number of
 280 items recaptured per stormwater inlet according to its morphology (see the corresponding colors in Figure 1b)

281

282 The number of recaptured items highly varied according to stormwater inlets. For 3 inlets (JV3, JV5 and
 283 JV7, Figure 1c), neither bottles/cans, nor sweet wrappers were recaptured. Two of them were underflow
 284 baffle inlets. During the first experiment, no inlet exhibited a 100% recovery rate of the bottles/cans.
 285 For 4 inlets (PS1, PS3, PS5 and JV4, Figure 1c), the number of recaptured items was similar during both
 286 experiments. For all other inlets, the number of recaptured items was highest for sweet wrappers.
 287 Besides, the recovery rate of sweet wrappers reached 100% for 2 opening curb inlets (JV2 and PS4,
 288 Figure 1c). No trend according to the distance between the stormwater inlets and the outlet was observed
 289 (Table S3).

290

291 **3.3. Litter fluxes in stormwater**

292 Given the litter amount collected during the investigated period, 29.1 kg/yr of litter are in total released
293 in the Gohards stream, representing around 6 g/inhabitant/yr and 0.4 kg/imp.ha/yr. Plastic litter fluxes
294 represent 14.1 kg/yr, or around 3 g/inhabitant/yr and 0.2 kg/imp.ha/yr (Table S6).

295 Among these litter fluxes, considering the masses of items that can be attributed to specific activities
296 within the park around the retention basin (section 3.1.), 10.7 kg/yr may be attributed to direct inputs
297 (37% of total litter fluxes) in the basin. Considering the masses of the typical wastewater items (section
298 3.1.), 0.6 kg/yr may be attributed to wastewater releases from the misconnected houses (2% of total litter
299 fluxes). However, such contributions include few plastic items, i.e. 0.4 kg/yr from direct inputs and 0.5
300 kg/yr from wastewater releases (3% and 4% of total plastic litter fluxes, respectively, Table S6). At least
301 61% of the litter fluxes and 93% of the plastic litter fluxes may therefore be attributed to stormwater
302 runoff.

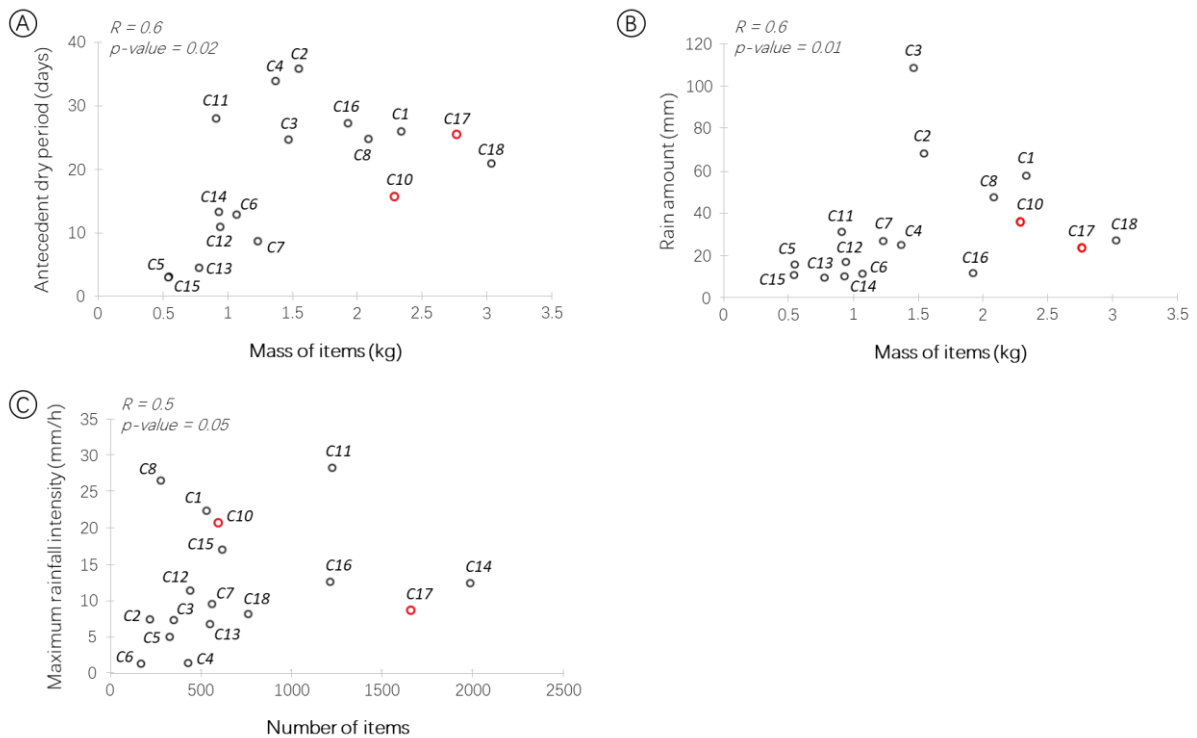
303

304 3.4. Relationship with hydrometeorological data

305 Campaigns integrated various hydrometeorological conditions. Excluding C9 for which the rain amount
306 was not sufficient to consider a rain event generating runoff according to the selection program,
307 campaigns integrate between 1 and 7 rain events and dry periods ranging from 3 to 36 days. The total
308 rain amounts ranged from 3 to 108.6 mm with rainfall intensities varying between 2.4 to 48.6 mm/h. For
309 the campaigns during which flow discharges were accurately recorded (C4, C6, C8, C10 to C13, C15
310 and C16), the maximum flow discharges generated at the outlet ranged from 188 to 3,008 L/s and runoff
311 volumes ranged from 1,178 to 11,416 m³ per event. Reported to these volumes, litter and plastic
312 concentrations ranged from 168 to 1,181 mg/m³ and from 47 to 681 mg/m³, respectively (median values
313 equal to 250 mg/m³ and 182 mg/m³, respectively; Tables 1 and S7).

314 Excluding C9, the collected masses of items were significantly correlated with the antecedent dry period
315 and with rain amount (Figure 5a and b). The number of transported items was positively correlated to
316 the maximum rainfall intensity (Figure 5c). A seasonality appears with increasing amount of litter (by

317 count and by mass) collected at the stormwater outlet in summer (Figure 2a) as a result of increasing
 318 dry periods and more intense rain events due to thunderstorms.



319
 320 **Fig. 5** Mass of items collected during each campaign (C1 to 18) according to A) the antecedent dry period and B) the rain
 321 amount. C) Number of items collected during each campaign (C1 to 18) according to the rain event maximum intensity (median
 322 value in case of several rain events). Campaigns for which an overflow of the retention basin was observed are represented
 323 with red circles. For each correlation, Spearman correlation coefficients and associated p-values are indicated

324

325 4. Discussion

326 4.1. Stormwater as a transfer pathway for urban litter

327 Item typologies and brands identified at the stormwater outlet were consistent with the activities of the
 328 Pin Sec and Jules Verne catchments, i.e. transport facilities, public places, bar/tobacco, fast-food
 329 restaurants, stores and a hospital. The predominance of smoking and food-consumption related items,
 330 the top 3 industrial groups of smoking related items as well as the most frequent brand of the food-
 331 consumption related items were similar on the urban surfaces of these catchments (Ledieu et al. 2024).
 332 Urban litter is therefore a major source of litter in waterways. In fact, the most littered items are broadly

333 similar on urban surfaces (Martinez and Griffiths 2023; Ledieu et al. 2024) leading to a general
334 predominance of smoking and food-consumption related items in stormwater and receiving urban
335 streams in France (Tramoy et al., 2022a, b), in the Netherlands (Tasseron et al. 2020), in New Zealand
336 (Martinez and Griffiths 2023), in Australia (Sherow et al. 2023), or in South Africa (Weideman et al.
337 2020).

338 The litter fluxes calculated in this study are in the same range as other studies investigating litter fluxes
339 in stormwater from French urban areas, i.e. a few g/inhabitant/yr, between 0 and 1 kg/ha/yr or hundreds
340 of mg/m³, and these ranges are higher than the only known fluxes calculated in a combined sewer
341 network (Tramoy et al. 2022b, Table 1). The calculated plastic litter fluxes orders of magnitude (Table
342 1) are actually similar to the emissions estimated for a number of European rivers (i.e. 1-10
343 g/inhabitant/yr; González-Fernández et al., 2021). In the case of the Gohards stream, direct releases of
344 items and wastewater contributions from misconnected houses are suspected (e.g. sanitary towels and
345 wipes) but their contribution are assumed to be low, especially regarding plastic litter fluxes (Table S6).
346 In fact, at least 61% of the total litter fluxes and 93% of the plastic litter fluxes measured in the retention
347 basin are transported by stormwater. It confirms that runoff leaching roadways and sidewalks is a major
348 pathway for litter towards receiving waterways (Weideman et al. 2020; Pasternak et al. 2021; Tramoy
349 et al. 2022b; Martinez and Griffiths 2023). Besides, Weideman et al. (2020) quantified much higher
350 litter fluxes in South Africa (Cape Town) than other studies (Table 1) probably resulting from higher
351 amounts of urban litter due to a poor waste management. This raises questions about the current
352 prioritization of separate sewer systems to achieve the objectives of reducing the impact of wastewater
353 treatment on aquatic environments. In the case of the Gohards stream, the retention basin limits the
354 transfer of litter to the stream except in the case of overflows, but most stormwater networks have no
355 specific control or prevention. Moreover, it can be assumed that litter has sanitary and ecotoxicological
356 impacts even accumulated in the retention basin.

357

358

360 Table 1 : Annual total litter and plastic litter fluxes normalized per inhabitants (in g/inhabitant/yr), per drained surfaces (in
 361 kg/ha/yr) or per impervious surfaces (in kg/imp.ha/yr), and concentrations (in mg/m³), in catchments from different countries
 362 according to their sewer systems (SW = stormwater, C = combined) and land uses (Ind. = industrial, Com. = commercial, Res.
 363 = residential).

			Per inhabitant (g/ inhabitant /yr)	Per surface (kg/ha /yr)	Per impervious surface (kg/imp.ha/yr)	Per runoff volumes (mg/m ³)
Total litter fluxes						
Cape Town (South Africa)¹		Ind.	137.6			
		Com. & Res.	42.0			
		Res.	0.9			
Northland (New Zealand)²		Mixed	1.8			
Sucy-en-Brie (France)³	SW	Res.				28-182
Goussainville (France)⁴		Mixed	10-20	1		
Malaunay (France)⁴		Com.	2	0.1		
This study		Com. & Res.	6	0.3	0.4	158- 1,181
Grenoble (France)⁴	C	Res.	0.4	0.03	25	
Plastic litter fluxes						
Cape Town (South Africa)¹		Ind.	71.1			
		Com. & Res.	21.6			
		Res.	0.5			
Northland (New Zealand)²		Mixed	1.1			
Sucy-en-Brie (France)³	SW	Res.	19		1.7	7-134
Goussainville (France)⁴		Mixed	5-10	0.5		
Malaunay (France)⁴		Com.	2	0.1		
This study		Com. & Res.	3	0.1	0.2	47-681
Grenoble (France)⁴	C	Res.	0.1	0.006	5	

364 ¹Weideman et al., 2020; ²Martinez and Griffiths, 2023 ; ³Treilles et al., 2021; ⁴Tramoy et al., 2022b

365

366 4.2. Transport dynamic of litter through stormwater networks

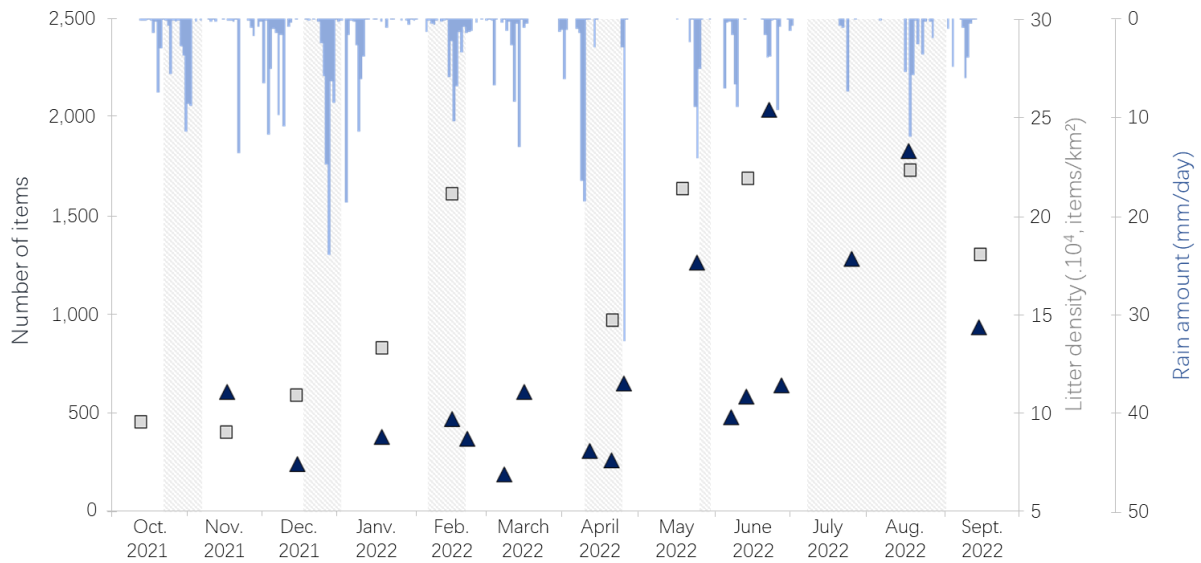
367 Even if urban areas concentrate plastic litter, this category of materials is even more predominant by
 368 count in urban stormwater (Martinez and Griffiths 2023; Sherow et al. 2023), like in receiving streams

369 (Weideman et al. 2020; Tasseron et al. 2020; Treilles et al. 2021; Tramoy et al. 2022a) and in rivers
370 (Crosti et al. 2018; González-Fernández et al. 2021; Cesarini et al. 2023). Most authors suggest a better
371 transport of these non-degradable, lightweight and buoyant items compared to paper, glass or metal
372 (Pasternak et al. 2021; Hadiuzzaman et al. 2022; Tramoy et al. 2022b; Cesarini et al. 2023). In this study,
373 the proportions of plastic by count increased from 62% on urban surfaces (Ledieu et al. 2024) to 92% at
374 the stormwater outlet, where the top 10 items only includes plastics (Figure 2c). The 5 types of paper
375 items frequently observed on the urban surfaces of the Pin Sec and Jules Verne catchments (see Ledieu
376 et al., 2024) are not transported, probably because of their degradation (Crosti et al. 2018; Pasternak et
377 al. 2021), except in case of intense rain events. The recurrence of foamed polystyrene fragments and
378 plastic tobacco pouches at the stormwater outlet (Figure 2c) while these were not commonly observed
379 on urban surfaces (Ledieu et al. 2024) also highlight the promoted transport of lightweight and buoyant
380 items. Moreover, capture/recapture experiments and the predominance of items < 2.5 cm in the top 10
381 (Figure 2c) confirmed an easier transport of small items (Pasternak et al., 2021). Cesarini et al. (2023)
382 suggested that the break-up processes of litter start before items reach the sea. In this study, the
383 increasing proportions of unidentified plastic fragments from the urban surfaces (9%, Ledieu et al.,
384 2024) to the stormwater outlet (24%, Table S5) even demonstrates that these processes start on urban
385 surfaces, probably due to the road traffic or other factors e.g. the cutting of grass (Ledieu et al., 2024).
386 As a result, their transport by stormwater is enhanced. Item composition and sizes play a key role in
387 their transport dynamic and litter transfer through stormwater networks is thus selective.

388 Litter fluxes transported by stormwater exhibit a seasonality in several studies (Treilles et al. 2021;
389 Tramoy et al. 2022a; Martinez and Griffiths 2023). In the case of the Pin Sec and Jules Verne
390 catchments, litter fluxes tend to increase in summer (Figures 2 and 6) when rain events are more intense
391 considering that high intensity events encourage the transport of a greater number of items (Figure 5c,
392 Tramoy et al., 2022a; Treilles et al., 2021). Hydrological parameters are however not sufficient to
393 explain this variability (Tasseron et al. 2020; Roebroek et al. 2022). As cleaning services do not recover
394 all the items, litter accumulate on urban surfaces, particularly in summer (Figure 6) when outdoor
395 activities are more intense and promote litter generation (Ledieu et al. 2024). Thus, the greater the time

396 interval between two rain events, the greater the quantity of litter exported (Kim et al. 2006) as
397 demonstrated by the increasing mass of items collected at the stormwater outlet with increasing
398 antecedent dry periods (Figure 5a). In contrast, studies monitoring stormwater inlets observe the highest
399 litter fluxes during wet periods with more rain events (Malik et al. 2021; Martinez and Griffiths 2023).
400 In fact, the 46% recovery rate of the capture/recapture experiments suggests that even if stormwater
401 removes items from urban surfaces, these were not necessarily transferred towards the outlet. The not
402 recaptured items could (i) have been recovered during a cleaning of the stormwater inlets, (ii) be stuck
403 in the sewer network, (iii) be transferred downstream the retention basin, or (iv) be accumulated at the
404 bottom of the basin. After overflows of the retention basin, a small percentage (3%) of tagged items was
405 recovered in the Gohards stream but no item was found far downstream. During dry weather, 5% of
406 tagged items (mostly cans) were identified at the bottom of the pond and recaptured. No item was
407 observed during the video exploration of some parts of the stormwater network (Figure S3). In fact,
408 some bottles/cans placed during the first experiment were still in some underflow baffle inlets when the
409 sweet wrappers were placed inside 7 months after. Litter may thus be blocked by structures (e.g.
410 selective inlets, Treilles et al., 2021) and/or create clogging (Basilico et al. 2020) leading to an
411 intermittent transport dynamic in urban stormwater networks (Figure 4a and b). Like observed in rivers
412 (Tramoy et al. 2020; Ledieu et al. 2022), items can have longer residence times in stormwater networks
413 than those considered in global models (Treilles et al. 2021).

414



415

416 **Fig. 6** Number of items collected (blue triangles) during each campaign according to the periods. Litter densities quantified on
 417 the urban surfaces of the catchments (grey cubes) for the similar period (from Ledieu et al., 2024), rain amounts and periods
 418 of school holidays (grey stripes) are represented

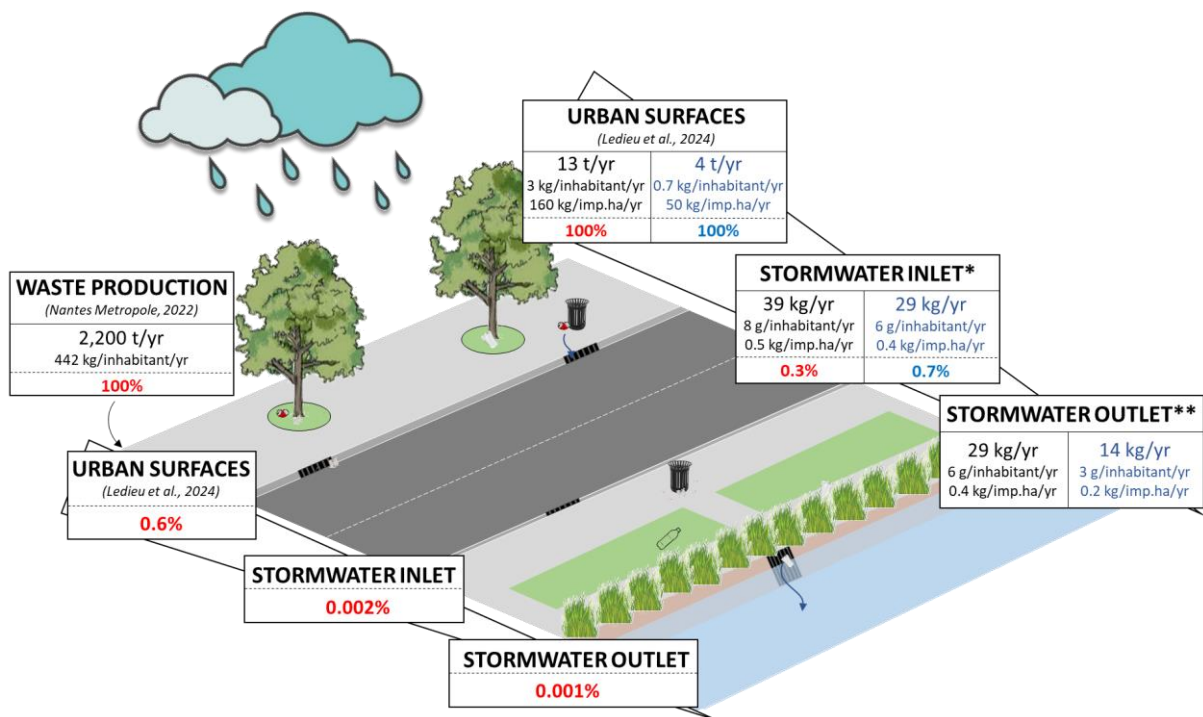
419

420 4.3. Litter fluxes through urban stormwater networks

421 The companion paper consisting in the assessment of litter on the urban surfaces of the present study
 422 area demonstrated that the total proportion of littered items only represented 0.6% of the total waste
 423 production of the Pin Sec and Jules Verne catchments (Ledieu et al., 2024, Figure 7). As highlighted by
 424 the impact of public place cleaning frequencies in Chicago (USA, Vincent and Hoellein, 2017) and in
 425 several French cities (Goussainville, Malaunay and Grenoble, Tramoy et al., 2022b), a major part of the
 426 litter stock on urban surfaces is removed by the cleaning services. Remaining items are mostly
 427 accumulated in green spaces (Ledieu et al. 2024) where their removal is limited (Gholami et al. 2020;
 428 Mellink et al. 2022). As a result, the estimated litter fluxes entering the stormwater inlets of the Pin Sec
 429 and Jules Verne catchments only represent 0.3% of the mass estimated littered on the urban surfaces. In
 430 comparison to the total waste production per inhabitant at Nantes Métropole, litter fluxes measured at
 431 the stormwater outlet represent 0.001%. This leak is higher for plastic litter considering their promoted
 432 transport by stormwater. The 0.7% of plastic leakages rates quantified in this study (Figure 7) are
 433 however far lower than the 15-40% considered by Jambeck et al. (2015) to estimate the riverine plastic

434 export into the sea. In Sucy-en-Brie (France), Treilles et al. (2021) actually quantified a plastic litter
 435 fluxes in stormwater corresponding to less than 0.03% of the amount consumed per inhabitant. The
 436 buffering effect of the stormwater network and the presence of selective inlets further reduce the litter
 437 fluxes that manage to reach the stormwater outlet. In this study, litter fluxes quantified at the stormwater
 438 outlet represent only half (46%) of the fluxes reaching the stormwater inlets as $\frac{3}{4}$ of them are equipped
 439 with grates and underflow baffles (Figure 1b). Nevertheless, more regular cleanings of stormwater inlets
 440 could further reduce litter fluxes as suggested by the long residence time (up to 7 months) exhibited by
 441 some bottles/cans. Moreover, it clearly appears through the results of this study that the most upstream
 442 actions (cleaning services) reduce more efficiently litter emission towards receiving waterways than
 443 when they reach the stormwater network. This low leakage rate also suggests that further reducing the
 444 plastic litter in waterways would mainly involve a reduction in their consumption.

445



446

447 **Fig. 7** Conceptual scheme of total litter and plastic litter fluxes (in blue) on the urban surfaces, at the stormwater inlet and the
 448 stormwater outlet of the Pin Sec and Jules Verne catchments. *Fluxes expressed at the stormwater inlet are calculated
 449 assuming that stormwater releases identified at the outlet represent 46% of the fluxes reaching the inlets. **Fluxes expressed
 450 at the stormwater outlet include the fluxes suspected from direct inputs and wastewater releases. The percentages
 451 represented by these leaks are expressed on the left in relation to the waste production per inhabitants (Nantes Métropole,
 452 2022), and on the right in relation to the masses of littered items in public places (taken from Ledieu et al., 2024 – Litter in
 453 French urban areas - Part 1).

454

455 4.4. Recommendations for the assessment of stormwater contribution to the litter
456 pollution in hydrosystems

457 Even if the litter fluxes transported by stormwater are relatively low compared to the waste production
458 and littering, these represent high litter loads transferred towards receiving waterways when considering
459 population of the catchments. In the urban litter studies, fluxes are expressed as a function of the number
460 of inhabitants or the impervious surface area of the catchment (in ha, Table 1). Using the number of
461 inhabitants takes greater account of the generation of litter, compared with the overall production of
462 waste per inhabitant. In contrast, using the impervious surface area takes a hydrological approach, taking
463 greater account of the transfer pathway, runoff.

464 At a national scale, extrapolated to the national number of inhabitants in France (i.e. 65.8 million in
465 2023; <https://www.insee.fr/fr/statistiques/5225246>), litter fluxes calculated at the stormwater outlet in
466 this study (Table 1) would represent an export of around 395 t/yr of litter, whose 197 t/yr of plastics. It
467 corresponds to the French annual input of plastics released from land estimated by González-Fernández
468 et al. (2021) but the extrapolation using the number of inhabitants is subject to certain biases. In fact,
469 litter is mainly the result of on-the-go consumptions and passersby contribute greater to the litter amount
470 than inhabitants (Kawecki and Nowack 2019; Ledieu et al. 2024). Moreover, littering trends cannot be
471 easily generalized. For example, Weideman et al. (2020) observed higher litter fluxes at the stormwater
472 outlets draining industrial and commercial areas than the one draining residential areas (Table 1),
473 consistently with the observations from urban litter studies (Keep Britain Tidy 2020; Gholami et al.
474 2020; Pietz et al. 2021; Youngblood et al. 2022; Xiong et al. 2022) including in the Pin Sec and Jules
475 Verne catchments (Ledieu et al. 2024). Nevertheless, in Australia, Sherow et al. (2023) observed lower
476 litter fluxes at stormwater outlets from industrial areas than from city centres, shopping areas and
477 transport hubs, and in New Zealand, Martinez and Griffiths (2023) observed higher litter fluxes from
478 hospital grounds, fast foods and retail than from hotel/motel, residential and commercial areas. To date,
479 there are few studies on the variation in litter fluxes between sites, and discrepancies in land use
480 definitions make interpretation of the results difficult. In addition, including information on litter

481 generation and waste management systems (waste collection and cleaning activities) in the litter studies
482 is essential to include such variables in the extrapolations.

483 Extrapolations using urban surface areas are also biased since only impervious surfaces contribute to
484 stormwater runoff. By only considering impervious surfaces, Treilles et al. (2021) actually quantified
485 higher fluxes in Sucy-en-Brie than in other French cities (Table 1). Considering the impervious surfaces
486 in mainland France (i.e. 3,300,000 ha, Loisiert and Petel, 2019), litter fluxes calculated at the stormwater
487 outlet in this study (Table 1) would represent 1,320 t/yr, of which 660 t/yr are plastics, released in French
488 hydrosystems. This is three times higher than the extrapolations using the number of inhabitants. An
489 approach using the impervious surface area appears more consistent with the concept of litter production
490 and transport. Nevertheless, the question of whether the total impervious surfaces should be considered
491 or only roadways and sidewalks (where there is potentially litter) remains open. In this study, buildings
492 were taken into account, resulting in impervious surfaces representing 76% of the catchment area,
493 compared with 27% in the study of Treilles et al. (2021). In addition, not all impervious surfaces in
494 urban areas are connected to separate sewers and little information is available on the potential additional
495 contribution of combined sewer overflows. On the scale of Greater Paris (183,000 ha, France), Treilles
496 et al. (2021) demonstrated that the impervious surfaces connected to separate sewers represented only
497 10% of the surface area (i.e. 19,000 ha), which considerably reduces the potential inputs of litter by
498 stormwater. Moreover, stormwater networks may be buried or open, which modifies the potential of
499 direct inputs of items. Finally, such extrapolations do not take spatial variations of hydrometeorological
500 parameters into account. Expressing litter concentrations as a function of runoff volumes (in mg/m^3)
501 may be a good way to include these variables.

502 It is thus difficult to extrapolate the contribution of stormwater to plastic litter pollution in waterways.
503 Litter fluxes transported by stormwater depend as much on litter generation on urban surfaces as on
504 runoff and potential obstructions. Detailed information on these parameters in further studies would
505 provide a better understanding of the impact of these factors in order to identify ways of combining them
506 to refine extrapolations. Finally, considering that the selective and intermittent transport dynamic of
507 litter in urban areas appears regulated by the same rules as in natural environments (e.g. the presence of

508 vegetation, an enhanced transport of lightweight plastic items and a transport promoted during intense
509 rain events), modeling litter transport through stormwater networks may be addressed by hydrological
510 or erosion models.

511

512 **Conclusions**

513 By concentrating small and lightweight plastic items, urban areas create a considerable hotspot of items
514 that can be transported by stormwater. Litter at stormwater outlets therefore reflect the global urban
515 plastic litter composition, i.e. mainly smoking and food consumption related items. In this study, the
516 plastic litter fluxes represent around 6 g/inhabitant/yr and 0.4 kg/imp.ha/yr. Even if these fluxes
517 normally remain in the retention basin, results of this study confirm that stormwater runoff is a
518 significant transfer pathway for plastic litter making their outlets considerable point sources of litter
519 towards receiving streams.

520 Litter fluxes can be highly variable depending on: (i) the stock of litter lying on urban surfaces, (ii) the
521 hydrometeorological variables, (iii) the item transport capacity, and (iv) the presence of stormwater
522 management structures limiting their transfer. These several influencing factors raise the question about
523 which parameter to use for extrapolating the results as considering the litter generation (normalizing per
524 inhabitants) or the transfer pathway (normalizing by the drained area) can lead to high variations in the
525 global estimations of litter fluxes. Litter transport dynamic is therefore not linear and difficult to interpret
526 but a way to integrate all these parameters in global models needs to be found.

527 Finally, this study illustrates the valuable impact of upstream actions to reduce the litter fluxes
528 transported by stormwater. Thanks to cleaning services, stormwater actually remove few proportions of
529 items compared to the amount littered on urban surfaces. Moreover, high litter loads remain accumulated
530 in green spaces. Consequently, in the case of the Pin Sec and Jules Verne urban catchments, only 0.3%
531 of the littered items and 0.7% of the littered plastics appear to reach the stormwater inlet and their
532 structures to limit the transfer of litter towards the sewer network (i.e. grates and underflow baffle)
533 further reduce these fluxes. Such conclusions imply that further fluxes reduction would require a

534 diminution in plastic consumption, in littering as well as a more regular maintenance of stormwater
535 inlets.

536

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671 The authors have no relevant financial or non-financial interests to disclose.

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673 **Author Contributions**

674 Johnny Gasperi, Bruno Tassin, Romain Tramoy, Clémence Bruttin, Eric Bouchet and Lauriane Ledieu
675 contributed to the study conception and design, and to the data analysis. Litter collection and
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