

Freshwater plastic pollution

Recognizing research biases and identifying knowledge gaps

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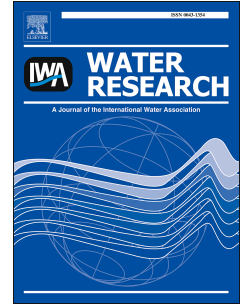
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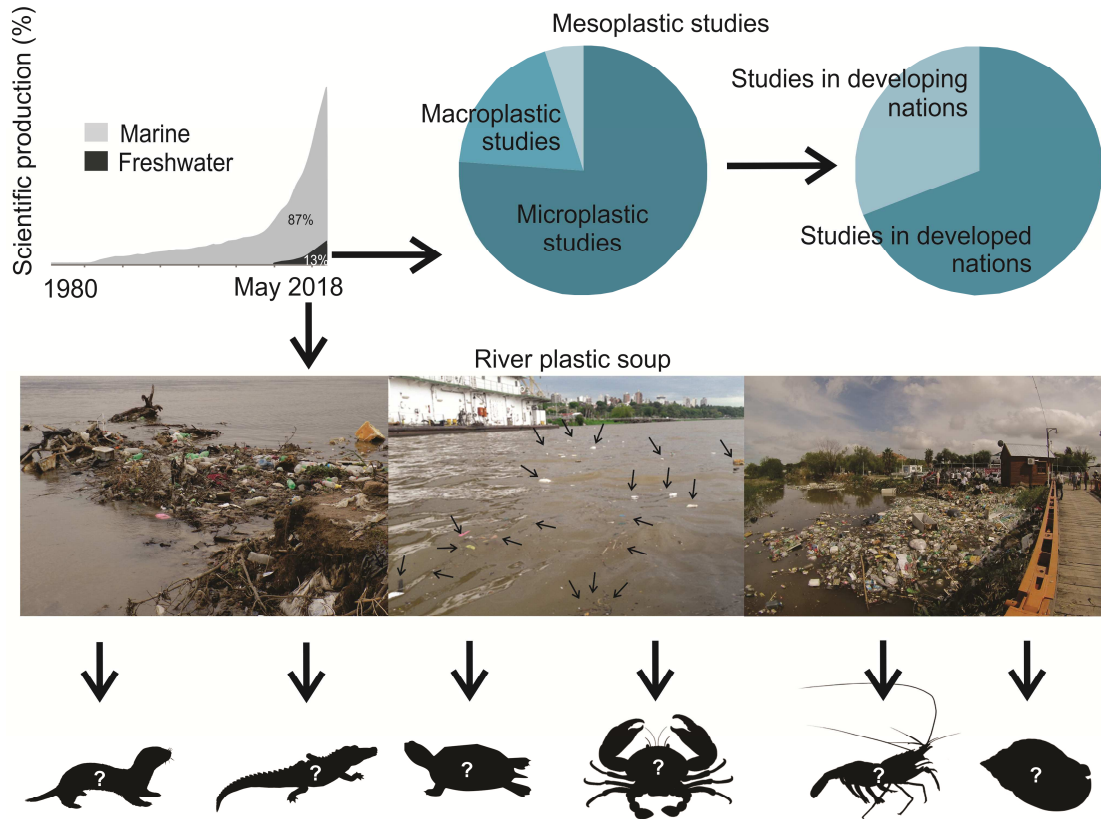
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ACCEPTED MANUSCRIPT

1 **Title**

2 Freshwater plastic pollution: recognizing research biases and identifying knowledge gaps

3

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10

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25 **Keywords:** plastic pollution, freshwater environment, macroplastic, developing country,

26 endangered fauna.

27 **Abstract**

28 The overwhelming majority of research conducted to date on plastic pollution (all size fractions)
29 has focused on marine ecosystems. In comparison, only a few studies provide evidence for the
30 presence of plastic debris in freshwater environments. However, owing to the numerous differences
31 between freshwater studies (including studied species and habitats, geographical locations, social
32 and economic contexts, the type of data obtained and also the broad range of purposes), they show
33 only fragments of the overall picture of freshwater plastic pollution. This highlights the lack of a
34 holistic vision and evidences several knowledge gaps and data biases. Through a bibliometric
35 analysis we identified such knowledge gaps, inconsistencies and survey trends of plastic pollution
36 research within freshwater ecosystems.

37 We conclude that there is a continued need to increase the field-data bases about plastics (all size
38 fractions) in freshwater environments. This is particularly important to estimate river plastic
39 emissions to the world's oceans. Accordingly, data about macroplastics from most polluted and
40 larger rivers are very scarce, although macroplastics represent a huge input in terms of plastics
41 weight. In addition, submerged macroplastics may play an important role in transporting
42 mismanaged plastic waste, however almost no studies exist. Although many of the most plastic
43 polluted rivers are in Asia, only 14% of the reviewed studies were carried out in this continent (even
44 though the major inland fisheries of the world are located in Asia's rivers). The potential damage
45 caused by macroplastics on a wide range of freshwater fauna is as yet undetermined, even though
46 negative impacts have been well documented in similar marine species. We also noted a clear
47 supremacy of microplastic studies over macroplastic ones, even though there is no reason to assume
48 that freshwater ecosystems remain unaffected by macro-debris.

49 Finally, we recommend focusing monitoring efforts in most polluted rivers worldwide, but
50 particularly in countries with rapid economic development and poor waste management.

51

52

53 **1. Introduction**

54 The presence of plastic debris has become a well-researched “hot topic” in the marine environment,
55 but up until recently was ignored in freshwater environments (Wagner et al., 2014; Eerkes-Medrano
56 et al., 2015). While plastic pollution monitoring data from freshwater environments is still in its
57 infancy, there is evidence showing plastic presence within such ecosystems since many years ago
58 (e.g. Williams and Simmons, 1996), and even within pristine and remote locations (e.g. Free et al.,
59 2014). The majority of plastic debris is used and disposed of on land, both terrestrial and adjacent
60 freshwater environments are subject to extensive pollution by plastics resulting from large amounts
61 of human litter (Horton et al., 2017). Similar to marine systems, major plastic pollution
62 contributions emanate from cities, poor waste management practices, fly tipping, improper disposal
63 or loss of products from industrial and agricultural activities, debris from the discharge of untreated
64 sewage, and storm water discharges, which also sweeps litter collected in storm drains into the
65 rivers (van der Wal et al. 2015; González et al. 2016). As a result, concerns about the impact of
66 plastics on freshwater ecosystems are legitimate and should receive more scientific attention
67 (Eerkes-Medrano et al., 2015; Lebreton et al., 2017; Li et al., 2017).

68 The limited information, however, has revealed that the abundance of microplastics is comparable
69 to marine contamination levels (Peng et al., 2017). Such abundance could likely lead to plastic
70 ingestion by the biota. Studies have reported plastic ingestion by wild freshwater organisms (e.g.
71 Sanchez et al., 2014; Faure et al., 2015; Biginagwa et al., 2016; Pazos et al., 2017). Plastic
72 concentrations have been reported in rivers (e.g. Lechner et al., 2014; Klein et al., 2015), lakes (e.g.
73 Fischer et al., 2016; Blettler et al., 2017), estuaries (e.g. Peng et al., 2017) and even on wastewater
74 treatment plants (e.g. Mintenig et al., 2017; Correia Prata, 2018). However, even a brief
75 examination of this freshwater plastics literature is enough to perceive that it is still scarce and does
76 not appear to be in accordance with global environmental priorities, endangered species, or social
77 demands. Moreover, freshwater plastic research seems to be inherently biased towards a country’s

78 state of development and disconnected as each study was conceived and conducted with its own
79 specific aims in mind.

80 In the present study we employed a bibliometric analysis of paper on the topic of freshwater plastic
81 pollution and compared it to the abundant literature on marine environments. Through our analysis
82 we thus identify knowledge gaps and research biases in freshwater plastic pollution literature; for
83 example, type of data urgently required, freshwater environments and fauna with no available data
84 to date and missing ecological impacts. Finally, we make a number of specific suggestions to fill
85 these knowledge gaps.

86

87 **2. Methodology**

88 The searching methodology (and criteria) was divided into two. On one side, a restricted searching
89 (using only one search engine and restrictive keywords) was conducted to compare the relative
90 scientific production in marine and freshwater environments (2.1). On the other side, an unrestricted
91 searching (using a broad range of search engines and keywords) was performed in order to detect as
92 many papers as possible regarding plastic pollution in freshwater systems (2.2).

93

94 *2.1. Marine versus freshwater literature comparison (restricted searching).*

95 This literature review was exclusively based on the Scopus search engine (<https://www.scopus.com>)
96 due to the great amount of marine literature. Scopus is a bibliographic database of academic journal
97 articles, covering nearly 20,000 titles of peer-reviewed journals from over 5,000 publishers.

98

99 *2.1.1. Searching criteria.*

100 We defined the Scopus search as follows: i) for marine environments: TITLE-ABS-KEY (“plastic
101 pollution” OR “plastic contamination” OR “plastic debris” AND sea OR coastal OR marine OR
102 maritime OR ocean). ii) For freshwater systems: TITLE-ABS-KEY (“plastic pollution” OR “plastic
103 contamination” OR “plastic debris” AND freshwater OR river OR lake OR estuary OR stream). No

104 limits in years (until May 2018) and subject area were considered. However, reviews, opinion
105 papers (no field-data), book chapters, conference papers and scientific reports were excluded from
106 the analysis.

107

108 *2.2. Freshwater literature unrestricted searching.*

109 We census and compiled all available scientific literature about plastic pollution in freshwater
110 environments using the following search engines: Scopus dataset (see above), Google Scholar
111 (<http://scholar.google.com/>), GetCITED (<http://www.getcited.org/>), PLOS ONE
112 (<http://www.plosone.org/>), BioOne (<http://www.bioone.org/>) and ScienceDirect
113 (<http://www.sciencedirect.com/>).

114

115 *2.2.1. Searching criteria.*

116 The selected criteria of search included related words like: “freshwater”, “inland water”,
117 “continental water”, “river”, “stream”, “creek”, “brook”, “lake”, “lagoon”, “pond”, “wetland”,
118 “estuary”, “reservoir”, “sewage”, “laboratory condition” AND “plastic”, “macroplastic” (i.e. ≥ 2.5
119 cm), “mesoplastic” (i.e. $2.5 - 0.5$ cm), “microplastic” (i.e. ≤ 0.5 cm) AND “pollution”,
120 “contamination”, “ingestion”, “entanglement”, “waste”, “debris”. We also included herein book
121 chapters, conference papers and scientific reports but reviews and opinion papers were excluded
122 from the analysis (no field-data). No limits in years (until May 2018), document type and subject
123 area were considered.

124

125 *2.3. Quality assessment and categorization.*

126 Subsequently, an exhaustive manual checking of the results (paper by paper) was performed to both
127 searches (sections 2.1 and 2.2) at the discretion of the authors of this study. This individual manual
128 checking was crucial to avoid study repetitions (for example, advanced results published in
129 congress but then fully published in journals), papers outside the topic of this study, unclear or

130 incomplete reports, etc. This step significantly reduced the final data-set showing that keywords
131 themselves do not necessary represent a reliable search parameter.
132 From each of the reviewed papers we identified: i) aquatic environment (marine or freshwater); ii)
133 authors; iii) country and development indicators (based on the World Bank list of economies,
134 2017); iv) plastic size fraction (micro, meso, and macroplastics) (note: studies can consider both one
135 or more fractions); v) freshwater environment (river, lake, estuary, reservoir, sewage and laboratory
136 condition); vi) compartment (water surface or column, shoreline or bottom sediments); vii) biota
137 impact/interaction; and viii) biotic community (fish, bird, mammal, reptilian, zoobenthos,
138 zooplankton, mollusk, bacteria, etc).

139

140 2.4. Data analyses.

141 The information was organized as a unique data-set. In order to compare studies in marine and
142 freshwater systems the cumulative number (%) and rate of growth (articles year⁻¹) of the scientific
143 production were estimated for both environments. This rate of growth was calculated from 2010 to
144 date. Simple statistics were used in order to create maps, tables and figures identifying countries
145 and regions that have been studied and those where research has not yet been conducted, impacted
146 biota in marine and freshwaters, plastic size fractions in freshwater systems, studied freshwater
147 environments and compartments. Major plastic polluting rivers were also identified in relation to
148 fisheries production and the lack of field data.

149

150 3. Results and discussion

151 3.1. Bias in marine and freshwater scientific production.

152 A total of 624 papers were found for marine environments based on the Scopus searching (see
153 section 2.1). However, only 440 (~70%) of them were suitable for the purposes of this study
154 (selected under authors' criterium). In order to keep comparable search criteria, a similar analysis

155 was carried out for freshwater literature (i.e. Scopus searching) with a total of 105 papers identified,
156 but only 64 of them were appropriate to be used in this study.

157 While the number of published studies on plastic pollution in marine environments has increased
158 dramatically in the last decades, considerably less studies have assessed this topic within freshwater
159 systems. While this tendency has been suggested by other authors (Wagner et al., 2014; Eerkes-
160 Medrano et al., 2015; Blair et al. 2017), it has not been fully quantified thus far. We found that 87%
161 of plastic pollution studies are related to the marine environments and only 13% to freshwater
162 systems, with a rate of growth of approximately 41 vs. 7 papers year⁻¹ for marine and freshwater
163 environments, respectively (Figure 1).

164

165 >>>>> Figure 1.

166

167 Thus, the rate of growth in marine scientific production is more than 5 times higher than in
168 freshwater ecosystems. Evidently, scientific efforts are still too focused on marine environments.
169 The limited information, however, suggests that plastic pollution in freshwater systems is
170 comparable to marine contamination levels. While diminishing aesthetic value of rivers and lakes,
171 plastic debris is also likely to cause freshwater biodiversity loss and pose threats to human health
172 through fish and water consumption (Peng et al., 2017; Tyree and Morrison, 2017). In this context,
173 there is no reason that justifies the continued lack of studies in freshwater environments.

174

175 *3.2. Bias in Global coverage.*

176 In addition to the 64 papers found for freshwater plastic research using Scopus, 42 peer reviewed
177 publications papers were found using different search engines (see section 2.2). Thus, a total of 106
178 plastic pollution studies were recorded in freshwater environments worldwide. These studies were
179 distributed between 23 total countries with 73 studies carried out in developed countries and 33 in
180 developing ones (Figure 2).

181

182 >>>>> Figure 2.

183

184 Figure 2 revealed that data on freshwater plastics is fragmented across continents and completely
185 absent from the majority of countries. Most of the studies were performed in Europe and North
186 America (67%). Only a few studies were detected in Asia (most of them in China; 16%), South
187 America (Brazil, Argentina, Colombia and Chile; 11.8%), Africa (South Africa and Tanzania; 4%)
188 and Australia (2%; Figure 2). China is the second most dominant country in terms of scientific
189 production (and by far the leading of the fast developing countries). However, its scientific effort is
190 still poor considering China's population (1.41 billion, based on United Nations statistics), total area
191 (9,597 M km²), GDP Annual Growth Rate (the Chinese economy expanded by 6.8 percent year-on-
192 year in the first quarter of 2018, the same pace as in the previous two quarters; World Bank open
193 data, 2018) and mainly the fact that 7 of the world's top 20 of the reported plastic polluted
194 rivers flow through major Chinese cities. Models suggest that only these Chinese rivers contribute
195 around two thirds of plastic released through rivers into the oceans (Lebreton et al.,
196 2017). Moreover, according to our review, there is no field data about notable Asian rivers, such as
197 the Ganges and Mekong Rivers, that are likely polluted by plastics.

198 According to the international literature, reviews about plastic pollution in freshwaters has been
199 conducted by Wu et al. (2018) in Asia, Khan et al. (2018) in Africa, Eerkes-Medrano et al. (2015)
200 and Breuninger et al. (2017) in North America and Europe, among others. However, an overview of
201 plastics in South America has been absent from the literature until now. Available publications in
202 this continent are: Costa et al. (2011), Possatto et al. (2011), Ramos et al. (2012), Dantas et al.
203 (2012) and Ivar do Sul and Costa (2013) in Brazil; Acha et al. (2003), Blettler et al. (2017) and
204 Pazos et al. (2017) in Argentina; Correa-Herrera et al. (2017) and Arias-Villamizar and Vazquez-
205 Morillas (2018) in Colombia; and Rech et al. (2015) in Chile. Through the analysis of these papers,
206 we detected that 5 studies focused on microplastic ingestion by fish, and 8 of them selected

207 estuaries as studies area. Microplastic ingestion by fish was the most selected topic of study in
208 South America. While fish were clearly impacted by plastic pollution (e.g. Pazos et al., 2017), no
209 other aquatic taxa were study in South America. Considering that 5 of the top 10 largest river in the
210 world belong to South America and their drainage areas combined represent $9,650 \times 10^3 \text{km}^2$, with a
211 mean annual discharge of $262,000 \text{m}^3 \text{s}^{-1}$ to the ocean, and a population that far exceed 100 M of
212 habitants, we alleged an unjustified lack of attention to this continent.

213 In short, from a total of 195 countries in the world only 23 have studied the plastic pollution in
214 freshwater systems. Therefore, we suggest that the existing information is still fragmentary and
215 biased by countries development level and not by environmental global necessities.

216

217 *3.3. Bias between research in developed and developing countries.*

218 Sixty-nine percent of the recorded studies were carried out in developed countries and the 31%
219 remaining in developing ones (Table 1). Research on freshwater plastic pollution is a relatively new
220 topic and most efforts have been carried out in industrialized countries (Figure 2). This level of
221 disparity is not surprising since in the rankings of the top 10 best nations in sciences only one is an
222 emerging economy (China; The Editors, 2017). However, this unbalance is particularly significant
223 from an environmental and social point of view, since waste collection, processing and final waste
224 disposal still represents a problem in many low-middle income countries (Mohee et al., 2015).

225

226 >>>>> Table 1.

227

228 Increasing population levels, booming economy, rapid urbanization and the rise in community
229 living standards have greatly accelerated the municipal solid waste generation rate in developing
230 countries (Minghua et al., 2009). According to reports published by United Nations (United Nations
231 Human Settlements Programme, 2016) and the World Bank (Hoornweg et al., 2012), the systems
232 used for solid waste management in least developed countries are not fully suitable to handle the

233 current and future volume of waste generation. This is particularly true in urban informal
234 settlements, which are often in the most hazardous locations such as river floodplains. Open
235 uncontrolled dumping is still the most common method of solid waste disposal in such countries,
236 from which plastics can be introduced into water bodies. This is particularly significant since the
237 greater inland fisheries are located in developing countries (with the exception of the Russian
238 Federation; Table 2).

239

240 >>>>> Table 2.

241

242 The largest fish production in the world is placed in China by far (FAO, 2016). This is followed by
243 India, Bangladesh, Myanmar and Cambodia. All these fisheries belong to Asia, but our analysis
244 shows an apparent lack of field studies evaluating the effect of plastic pollution on fish in these
245 polluted rivers (Table 2). Note that 18 of the top 20 plastic polluted rivers, from global models of
246 plastic load inputs, are located in the major inland fish producer countries. In addition, the 16
247 countries listed in this table represent 80% of the total inland waters fish capture production around
248 the world (FAO, 2016). Inland fisheries are extremely important since hundreds of millions of
249 people around the world benefit from low-cost protein, recreation, and commerce provided by them,
250 particularly in developing countries where alternative sources of nutrition and employment are
251 scarce (McIntyre et al., 2016). Table 2 shows some crucial facts: i) the greater inland fisheries are
252 located in developing countries of Asia (mainly in China and India); ii) the major inland fisheries
253 are located in the top 20 plastic polluted rivers (as estimated by Lebreton et al. 2017, through global
254 models of plastic load inputs), with the exception of the Magdalena (Colombia) and the Tamsui
255 Rivers (Taiwan); iii) there is a clear lack of field evidence about the effect of plastic pollution on
256 fish in the most polluted rivers. These facts reveal a double problem. Firstly, the top 20 plastic
257 polluted rivers (as modeled by Lebreton et al., 2017) are located in the major inland fisheries
258 (belonging to developing countries, particularly Asia's economies). Secondly, a few field studies

259 evaluating the impact of microplastics on fish for consumption is definitely not enough considering
260 the human health and economic implications.

261 The above emphasises the need to focus monitoring and mitigation efforts in polluted rivers,
262 particularly in countries with rapid economic development, large inland fisheries and poor waste
263 management.

264 Finally, a worrying level of plastic pollutants was found inside fish in the few rivers where plastic
265 ingestion was studied (e.g. Pazos et al., 2017). In this sense, we hypothesize that fish from the rivers
266 mentioned in the Table 2 could be contaminated by plastics as well. As a result, there is an urgent
267 need to study plastic impact on fisheries given the economic importance and threats on human
268 health.

269

270 *3.4. Bias in species selection.*

271 The impact of plastic pollution on biota has been better studied in marine environments, involving
272 many biotic groups and species (particularly birds; Table 3). From a total of 440 recorded studies in
273 marine environments 178 (i.e. 40.5%) focused on impacts (or interactions) of plastic debris with
274 aquatic organisms, whereas 35 of the 106 recorded studies in freshwater systems (i.e. 33%)
275 analyzed the similar plastic-biota interactions in freshwaters (Table 3).

276

277 >>>>> Table 3.

278

279 Plastic research in the marine environment has focused on a wide range of organisms; birds (e.g.
280 Wilcox et al., 2015), fish (e.g. Steer et al., 2017), mammals (e.g. Garrigue et al., 2016), reptiles (e.g.
281 Schuyler et al., 2015), mollusks (e.g. Silva et al., 2016), decapods (e.g. Murray and Cowie, 2017),
282 bacteria (e.g. Keswania et al., 2016), algae (e.g. Yokota et al., 2017), and fungus (e.g. Paço et al.,
283 2017). However, Table 3 evidences the few studies evaluating impacts on freshwater fauna. Only a
284 few studies in freshwater fish, birds, bacteria (attached to micro-particles of plastics), mosses, algae

285 and invertebrates are available. Studies on microplastic ingestion by fish prevail in developing
286 countries (which is consistent with our previous results; Table 2). However the other taxa were
287 mainly studied in the developed world (Table 3). The recent interest of emerging economies in the
288 impact of plastic pollution on fish could be explained by the magnitude that inland fisheries have in
289 such economies (FAO, 2016). Artisanal and small-scale fisheries play a crucial role as a source of
290 livelihoods, food security and income for millions of people, particularly from developing countries
291 (Berkes et al., 2001) (see section 4.3). More than 90% of the output of inland fisheries comes from
292 developing countries and only 3.5% from industrial countries (Smith et al., 2005). Researchers from
293 developing economies are likely aware of this and accordingly focus their studies in the impact of
294 microplastics on fisheries.

295 No studies evaluating macroplastic impact/interaction on freshwater fauna (for example by
296 entanglement or as building material of bird nests) were recorded (Table 3). However, entanglement
297 of marine species in marine debris is a global problem affecting at least 200 species of mammals,
298 sea turtles, sea birds, fish and invertebrates (NOAA, 2014). This reveals a lack of attention on
299 macroplastics since examples of this type of interactions are visually obvious, particularly in
300 emerging countries where solid waste management are not well considered, as mentioned above
301 (Abarca-Guerrero et al., 2013).

302

303 *3.5. Bias in size fraction reporting.*

304 Referring to the size-ranges, plastic debris is commonly termed as micro- (≤ 5 mm), meso- (5 mm-
305 2.5 cm) or macroplastic (> 2.5 cm; Lippiatt et al., 2013), but there is not a standardized definition.
306 With regard the size fraction investigated amongst the different studies 76% of the surveys in
307 freshwater systems have studied microplastics, 19% macroplastics and only 5% mesoplastics (Table
308 1). While some studies pay attention to the three size-ranges, most of them (65%) have exclusively
309 focused on microplastics (i.e. deliberately ignoring macro and meso-debris) and only 7% entirely on

310 macroplastics (ignoring micro and meso-fractions). Studies on mesoplastics (excluding macro and
311 micro-debris) were not found.

312 Similar trends are seen in terms of global biases within the different size classes. Of all the
313 freshwater research surveyed for this paper, microplastics were most commonly investigated in the
314 developed and developing world (53% and 23% of the studies, respectively; Table 1). Similarly,
315 macroplastic surveys accounted for 14% in developed countries and only 5% in developing ones.
316 Considering the mismanagement of solid waste in least developed economies, which often end up
317 in water bodies as bottles, bags and packaging (section 3.3), the mentioned 5% represents another
318 bias in the current knowledge.

319 Additionally, many microplastic studies defined in this study as "non-exclusive" (Table 1) report
320 macroplastics (e.g. Moore et al., 2011; Sadri and Thompson, 2014; Baldwin et al., 2016; Cable et
321 al., 2017), but acknowledge the limitations in accurately quantifying these types of plastics since the
322 sampling designs of these studies were not specifically adapted to macroplastics. The relatively
323 small nets cross-sectional sampling areas and short exposure times may not be appropriate to
324 representatively capture macroplastic concentration.

325 Based on this literature review we suggest that the dominance of microplastic studies over
326 macroplastic ones could be explained by: 1) microplastics have been identified as one of the top 10
327 emerging issues by the United Nations Environment Programme (UNEP) in the 2005, 2014 and
328 2016 Year Books, which possibly encouraged microplastic studies. For example, Eerkes-Medrano
329 et al. (2015) and Gil-Delgado et al. (2017) explicitly mentioned this reason to justify their size-
330 range selection. 2) It has been proved that microplastics can impact freshwater fish (e.g. Lechner et
331 al., 2014; Sanchez et al., 2014; Biginagwa et al., 2016; Pazos et al., 2017), birds (Faure et al., 2012;
332 Holland et al., 2016; Gil-Delgado et al., 2017) and even zooplankton organisms (Rosenkranz et al.,
333 2009), which is economic and ecologically relevant. 3) Small plastic fragments may possibly have
334 leaching rates of exogenous chemicals (trace metals and organic pollutants) higher than those given
335 by macroplastics, due to their proportionally greater surface (Nakashima et al., 2012). Finally, 4)

336 microplastics are possible more widespread than macroplastics (Lithner, 2011). These four reasons
337 could explain why microplastics have received more attention than macroplastics by scientists.
338 However, we identified three reasons for the significance of macroplastics in freshwaters, and
339 which support further research: 1) over one hundred species of marine vertebrates have been
340 recorded as entangled in macroplastic debris (Allen et al., 2012; NOAA, 2014) such as pinnipeds
341 (Hanni and Pyle, 2000), sharks (Sazima et al., 2002), grey seals (Allen et al., 2012), turtles and
342 seabirds (using plastic garbage as nesting material) (de Souza Petersen et al., 2016). No studies have
343 been carried out describing macroplastics interaction/impact on freshwater fauna (see section 4.4).
344 Additionally, plastic bags, bottles, packaging straps and fishing lines in oceans are the most
345 common items which researchers have reported animals entangled in (Raum-Suryana et al., 2009;
346 Allen et al., 2012). All these macro-items are dominant in bottom sediments (Morritt et al., 2014),
347 shoreline sediments (e.g. Blettler et al., 2017) and water surface (e.g. Gasperi et al., 2014) of
348 freshwater environments worldwide. This suggests that fluvial species can be likewise impacted by
349 macro-debris. 2) Recently, pioneer studies have estimated the amount of plastic exported from river
350 catchments into the sea (Lebreton et al., 2017; Schmidt et al., 2017). Given the reduced field-data in
351 rivers, clearly identified in this study (Figures 1 and 2; Tables 1, 2 and 3), these authors developed
352 models based on mismanaged plastic waste, population density and hydrological data in river
353 catchments. The methodological strategy followed by these studies evidenced the scarcity of river
354 field-data collections, preventing direct estimations. Macroplastic data could be more important
355 than microplastic data for this type of studies, since macroplastics represent a significantly greater
356 input in terms of plastics weight (more than 100 times according to Schmidt et al., 2017). Lastly, 3)
357 microplastic surveys not necessarily are surrogate for macroplastic ones. Even when some authors
358 found a predictive relationship between micro and macroplastic items (e.g. Lee et al. 2013 on
359 marine marshes and beaches; González et al. 2016 on rivers); others reported no-associations
360 between both size particles, either in number or in resin composition (e.g. Blettler et al., 2017 in

361 freshwater lakes). Thus, macroplastics appear to have a particular distribution, potentially affecting
362 different habitat and species than microplastics, justifying its separate study.

363 These factors highlight the urgent requirement to increase the field-data bases about macroplastics
364 in freshwater environments, particularly in lotic environments of developing countries. We warn
365 about the necessity to fill this knowledge gap, given the potential damage caused by macroplastics
366 in freshwater environments.

367

368 *3.6. Bias in habitat diversity.*

369 The selected abiotic compartment of each paper was disproportionally represented amongst
370 freshwater systems (Table 4). However, research efforts on plastic pollution seem to be relatively
371 well distributed between rivers (31%), lakes (29.2%) and estuaries (21.2%).

372

373 >>>>> Table 4.

374

375 Conversely, studies in reservoir are an evident minority (only 1.8% and exclusively located in
376 China). Considering that about 16.7 million dams (with reservoirs larger than 0.01ha) exist
377 worldwide (Lehner et al., 2011) and 50% of larger rivers are affected by large dams (e.g. in rivers
378 such as the Upper Paraná River in Brazil contain more than 130 major dams) this deficiency should
379 be rectified.

380 Water surface and shoreline sediments were the most common abiotic compartment where plastic
381 accumulation was studied in freshwater systems. Both compartments represent more than 75% of
382 the studies (Table 4). Few studies have sampled plastic debris in the water column or in/close to the
383 bottom sediments. However, Morritt et al. (2014) focusing on the River Thames (London, United
384 Kingdom) demonstrated that a large unseen volume of submerged plastic is flowing along river
385 beds, representing an additional significant input which has been underestimated.

386

387 4. Conclusions and recommendations

388 Through analysis of the scientific literature pertaining to the presence of plastic debris in the
389 freshwater environments we identify an urgent need to increase the overall knowledge of this
390 research area. We quantitatively confirmed the dominance of plastic pollution studies in marine
391 environments over freshwater-focused research. Concerns about the impact of plastics on
392 freshwater ecosystems were legitimated through this review, as well as more opinion-orientated
393 publications, and therefore it must receive more scientific attention. Notably, we detected biases in
394 where and how studies are conducted that do not necessarily correlate to levels of expected
395 pollution or environmental priorities. Such biases likely result from socio-economic differences
396 between developed and developing nations. Furthermore, we also detected biases in the species
397 used as proxies for environmental monitoring, biases in habitat selection and biases in size-fraction
398 monitoring. Such partialities seem to be more related to authors' subjectivity than environmental
399 necessities. Six specific findings are outlined below with recommendations to rectify these
400 knowledge gaps.

401

402 1) The majority of plastic pollution studies in freshwaters were carried out in Europe (Western-
403 Central Europe) and North America (United States and Canada). However, it is necessary to enlarge
404 the scientific efforts in Asia and South America, particularly in low-middle income countries.
405 Increasing population levels, booming economy and rapid urbanization have greatly accelerated the
406 plastic waste generation rate, while treatment, recycle alternatives, recovery routes and final
407 disposal are still deficient in many developing countries within these continents.

408

409 2) The major inland fisheries (belonging to developing countries, particularly Asia's economies) are
410 located in the top 20 plastic polluted rivers. However, extremely few field-data or studies evaluating
411 plastic impact on fisheries are available from these rivers. There is an urgent need to focus

412 monitoring and mitigation efforts in the most polluted rivers or where inland fisheries are crucial for
413 local consumption and economies.

414

415 3) Unlike in marine, we detected a lack of studies analyzing the impact of microplastic pollution on
416 freshwater mammals, reptiles, macrocrustaceans and bivalves. Similarly, no studies evaluating
417 macroplastics impact (or interaction) on freshwater fauna (e.g. by entanglement or as building
418 material of bird nests) were recorded. Both observations suggest, once again, the limited
419 development of freshwater research.

420

421 4) We detected a dominance of microplastic studies over macroplastic studies in freshwater
422 environments worldwide, even though there is no reason to assume that these ecosystems remain
423 unaffected by macro-debris. In addition, assuming that rivers may play an important role in
424 transporting mismanaged plastic waste from land into the ocean, measurements of river
425 macroplastic debris are urgently required. Likewise, submerged macroplastics flowing near to the
426 river bed should be also quantified to avoid underestimations.

427

428 5) In the context of the global boom in hydropower dam construction worldwide (particularly in
429 developing countries), studies evaluating plastic pollution are essential to understand its potential
430 for reservoirs to act as garbage retainers.

431

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436

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658

659 **Figure captions**

660

661 **Figure 1.** Comparison between plastic pollution studies performed in marine and freshwaters,
662 showing total scientific publication and rate of growth in both environments since January 1980 to
663 May 2018.

664

665 **Figure 2.** World map showing number of studies about freshwater plastic pollution per country.
666 Color scale: dark blue to light blue scale stand for more to less number of studies. Where, United
667 States (US): 18; China (CN): 14; United Kingdom (UK): 13; Germany (DE): 9; Italy (IT): 7;
668 Canada (CA): 7; Brazil (BR): 6; France (FR): 5; Austria (AT): 4; Argentina (AR): 3; Netherland
669 (NL): 3; Switzerland (SW): 3; South Africa (ZA): 3; Australia (AU): 2; Colombia (CO): 2;
670 Denmark (DK): 1; Spain (ES): 1; Tanzania (TZ): 1; Chile (CL): 1; Mongolia (MN): 1; India (IN): 1;
671 Vietnam (VN): 1; and Sweden (SE): 1 study. “-p”: plastic. Note: exceptionally some studies
672 covered more than one country.

Table 1. Percentage of freshwater studies carried out in developed and developing countries to each plastic size fraction. And percentage of macro, meso and microplastic studies in freshwater environments, detailing percentage of papers considering only one “exclusive” fraction size (i.e. one merely plastic size fraction was studied) and more than one fraction size (“non-exclusive”).

Country development	Total (%)	Size fraction	Studies (%)	Size fraction	Total per size fraction (%)	Type	Studies (%)
Developed	69	Microplastic	53	Microplastic	76	Exclusive	57
		Macroplastic	14			Non-exclusive	16
		Mesoplastic	2	Macroplastic	19	Exclusive	6
Microplastic	23	Non-exclusive	15				
Developing	31	Macroplastic	5	Mesoplastic	5	Exclusive	0
		Mesoplastic	3			Non-exclusive	6

Table 2. Major inland fisheries producer countries in relation with the most plastic polluted rivers and field studies about fish plastic ingestion. *FAO (2016); **Lebreton et al. (2017).

Major inland fish producer countries	Fish capture, period 2003-2014 (average tones)*.	Top 20 plastic polluted rivers per country (ranking number)**.	Field studies evaluating plastic ingestion by fish.
China	2,229,652	Yangtze (1), Xi (3), Huangpu (4), Mekong (11), Dong (13), Zhujiang (17), Hanjiang (18)	2 (Taihu Lake in the Yangtze Delta)
India	1,017,539	Ganges (2)	0
Bangladesh	969,273	Ganges (2)	0
Myanmar	867,435	Irrawaddy (9), Mekong (11)	0
Cambodia	398,896	Mekong (11)	0
Uganda	398,646	-	0
Indonesia	339,872	Brantas (6), Solo (10), Serayu (14), Progo (19)	0
Tanzania UR	305,854	-	1 (Victoria Lake)
Nigeria	269,717	Cross (5), Imo (12), Kwa Ibo (20)	0
Egypt	256,437	-	0
Brazil	242,148	Amazon (7)	4 (Goiana Estuary)
Russia	231,044	-	0
Congo DR	224,930	-	0
Thailand	212,455	Mekong (11)	0
Viet Nam	199,306	Irrawaddy (9), Mekong (11)	0
Philippines	174,585	Pasig (8)	0

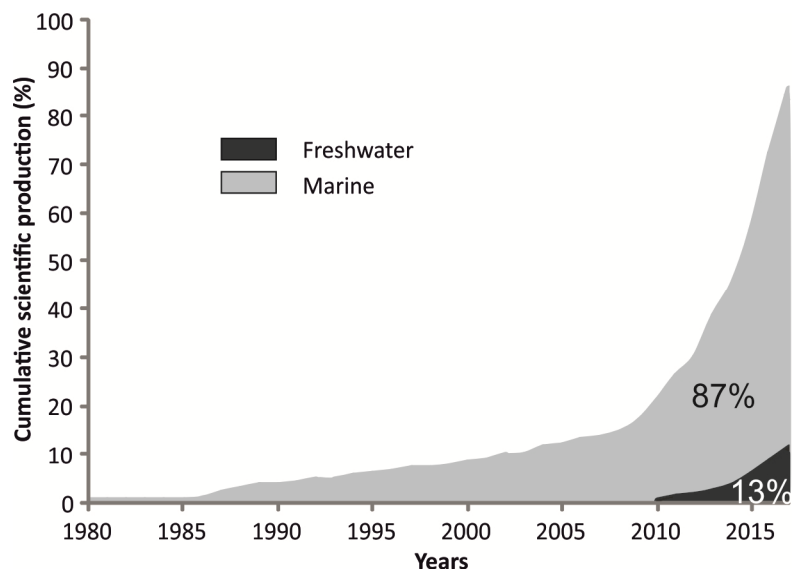
Table 3. Marine and freshwater studies considering impacts and interactions between plastics and organisms. ¹Biotic groups impacted by macroplastics (entanglement). ²Macroplastics used as building material by birds. ³Scopus searching (see Methodology). ⁴Unrestricted searching (see Methodology; 2.2). Note: some studies covered more than one fauna group.

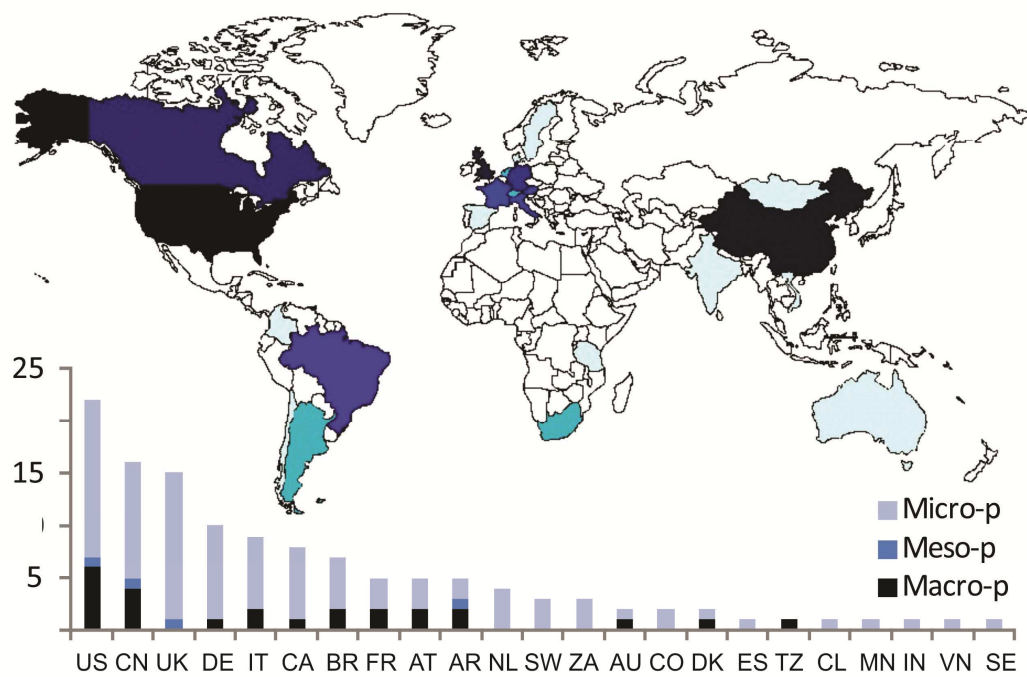
Biotic groups	N° of studies		
	Marine	Freshwater	
		Developed countries	Developing countries
Fish	35	10	7
Bird ^{1:2}	59	3	1
Mammal ¹	11	0	0
Turtle	17	0	0
Zoobenthos	15	3	1
Zooplankton	7	7	0
Mollusk	10	1	0
Decapods	4	0	0
Bacteria	13	3	0
Fungi	1	0	0
Alga	6	2	0
Moss	0	1	0
Total studies	178 (40.5%)	35 (33%)	

n= 440 (marine³) studies; n= 106 (freshwater⁴)

Table 4. Percentage of studies classified according to the freshwater environment and the abiotic compartment. Where: s= sediments; w= water.

Environment						
	River	Lake	Estuary	Laboratory	Sewage	Reservoir
N° of studies (%)	31	29.2	21.2	11.5	5.3	1.8
Abiotic compartment						
	W. surface	Shoreline s.	Bottom s.	W. column		
N° of studies (%)	45.7	30.9	12.3	1.11		





Highlights

- 1) There is a dominance of plastic pollution studies in marine over freshwater systems.
- 2) Of the existing freshwater studies, most come from developed countries.
- 3) Plastic pollution in the main inland fisheries rivers remains nearly unstudied.
- 4) We detected an evident supremacy of microplastic over macroplastic studies.
- 5) We identified the freshwater fauna groups not yet studied.