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Plastic transport in a complex confluence of the Mekong River in Cambodia

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Abstract

Field data on plastic pollution is extremely limited in Southeast Asian rivers. Here we present the first field measurements of plastic transport in the Mekong, based on a comprehensive monitoring campaign during the monsoon season in the confluence of the Mekong, Tonle Sap, and Bassac rivers around Cambodia's capital (Phnom Penh). For improved accuracy in the estimation of plastic loads and distribution, we combined Neuston net multipoint cross-sectional water sampling with acoustic Doppler current profiler high resolution measurements. During the wet season, around 2.03×10^5 kg d^{-1} of plastic were released from Phnom Penh into the Mekong, equivalent to 89 g d^{-1} capita^{-1}, or 42% of all plastic waste generated in the city. Most plastic mass moved downstream at the surface. A smaller portion of plastics is mixed deep into the water column, potentially retained in the rivers, breaking down and resuspending over time. Overall, plastic waste from Phnom Penh and transported by the Mekong is a significant contribution to Southeast Asia's plastic release into the ocean. This pollution represents a crucial risk to people in the region, as their livelihoods depend on fisheries from these water bodies.

1. Introduction

Southeast Asia is considered a major contributor of global plastic pollution, as Asian rivers may release up to 86% of the global annual plastic input into the oceans, especially during the East Asian monsoon (Jambeck *et al* 2015, Lebreton *et al* 2017, Schmidt *et al* 2017). These modeling results are widely acknowledged; yet, supporting field data in the region are limited to macroplastics (Lahens *et al* 2018, van Emmerik *et al* 2019a, 2019b). Further, most of the largest rivers in the world, many of which are key polluters as well, have not yet been monitored. In fact, the results of the few existing studies on the contribution of those rivers to global pollution are highly contrasting (Zhao *et al* 2014, Xiong *et al* 2019, Napper *et al* 2021, Singh *et al* 2021) and a recent model contradicts its predecessors suggesting that over 1000 (rather than 10) rivers are responsible for most of the plastic emissions to the ocean (Meijer *et al* 2021).

The Mekong River has the 10th largest water discharge in the world (Adamson *et al* 2009), and potentially the 8th or 11th highest plastic mass load input to the ocean (Lebreton *et al* 2017, Mai *et al* 2020). At Cambodia's capital, Phnom Penh, the Mekong forms the Chaktomuk confluence with the Tonle Sap and Bassac rivers. The Tonle Sap river experiences a seasonal flow reversal of more than 10000 m^3 s^{-1} driven by the hydraulic head difference between the Tonle Sap lake and the Mekong River, making it one of the most complex large-scale flow reversal systems on Earth (Arias *et al* 2012). This hydrological system is the primary driver of one of the world's largest freshwater fisheries and provides millions of people with food and income (Sabo *et al* 2017). Plastic occurrence in Cambodia and the Mekong Delta have not been monitored, but plastics are likely abundant in the region; a recent modeling study estimated that 221 700 tons of plastic entered the Tonle Sap basin from 2000 to 2020 (Finnegan and Gouramanis 2021). This is concerning, as plastics present risks to human health and livelihoods (Horton *et al* 2017, Liu *et al* 2020a), and aquatic biota are known to ingest plastics (Silva-Cavalcanti *et al* 2017, Bellasi *et al* 2020).

Plastic release into rivers and transport dynamics of plastic are exacerbated by human activities and watershed hydrology (Dris *et al* 2018, Horton and Dixon 2018, Windsor *et al* 2019). Retention and resuspension mechanisms as well as cross-sectional movement highly impact the spatial and temporal scale of plastic transport to the ocean (Liedermann *et al* 2018, Xiong *et al* 2019, Haberstroh *et al* 2021a, 2021b). Our study—the first field-based quantification of plastic pollution in the Mekong River and tributaries—focused on plastic pollution originating in Phnom Penh, in view of its impact on the Mekong's socio-environmental system. This study was guided by two questions: (a) How much plastic is released within the city of Phnom Penh and where is it transported to? (b) How are spatial plastic distribution and transport affected by wet season hydrology and the river confluence?

2. Methods

2.1. Study area

The study was carried out around the Chaktomuk confluence of the Mekong, Tonle Sap and Bassac rivers at Phnom Penh, Cambodia (figure 1). This rapidly growing city has a population of over 2 million and a population density of 3363 people km^{-2}. Where managed, the majority of solid waste is disposed into Dangkor landfill in the Dangkao district in the south of Phnom Penh, closely located to the Prek Tnot River, a tributary of the Bassac (Hoornweg and Bhada-Tata 2012, Seng 2015). About 83% of Phnom Penh had access to solid waste collection in 2015 (Cambodian Ministry of Environment 2019), a 23% increase from 2012 (Denny 2016). The plastic fraction in municipal solid waste increased from 6% in 1999 to 21% in 2015 (Seng *et al* 2011, 2018).

Phnom Penh is located 3870 km downstream of the Mekong's origin in China, and approximately 400 km upstream from the Mekong delta in southern Vietnam (Dietsch *et al* 2015). During the wet season (June–November), the Mekong is the only inflow into the city. Four sampling sites were selected outside the city boundaries to create a plastic budget of the city: (a) *Mekong Upstream*, (b) *Mekong Downstream*, (c) *Tonle Sap*, and (d) *Bassac* (figure 1, table 1).

2.2. Field data collection

Eight sampling events—two at each site—were conducted in August and September of 2019, during the peak of the wet monsoon season. The multi-point sampling method was developed for lowland rivers and captures cross-sectional variability (Haberstroh *et al* 2021a). We used a custom-built 500 μm Neuston net with a 0.5 × 1 m net frame, equipped with removable floats and weights to sample at the river surface and subsurface. An essential part of the sampling strategy was the use of a Sontek River Surveyor acoustic Doppler current profiler (ADCP), a multibeam sensor mounted on a floating board that measures current velocities at two different frequencies, georeferenced with an integrated GPS. With the ADCP we created detailed cross-sectional flow profiles, captured local discharge and determined local flow velocities to calculate sampling volume. Surface samples were collected across the river width (0.2 m net depth) and four depth samples through the water column in the river center at each site. Sampling depths were 3 m, 6 m, 9 m, 12 m, and 0.5 m/9 m in the Mekong and Tonle Sap sites, and 1.5–2 m, 3–4 m, 5–6 m, and 8 m in the Bassac (see table S2 (available online at stacks.iop.org/ERL/16/095009/mmedia) and figure S3 in supplementary materials for details). Altogether, 80 samples were collected, 9–11 samples per sampling event. Sampling was conducted from semi-stationary local fishing boats, deploying the Neuston net perpendicular to the flow at each point in the river cross-section for 10–15 min (with few exceptions due to high material loads, see table S3 in supplementary materials for sampling details).

2.3. Laboratory analysis

The laboratory methods have been developed and applied in studies in lowland rivers and are well suited for samples with high organic contents (Haberstroh *et al* 2021a). Each sample was rinsed over a 500 μm sieve, large organics were discarded and larger macroplastics (>1 cm) separated. The remaining sample was dried and sorted visually for plastic particles by two experienced team members. All plastics were categorized by size into macroplastics (>5 mm), large microplastics (<5 mm and >1 mm), and small microplastics (<1 mm). Count and mass were recorded by size class.

2.4. Raman analysis

A sub-sample of 482 particles below 5 mm was analyzed with a Jasco NRS4500 confocal scanning Raman microscope to determine polymer identity and their prevalence. We conducted confocal Raman mapping and characterized the resulting spectra with a combination of ad hoc, commercial, and open-source databases and manual inspection for characteristic Raman spectra of common polymeric groups.

2.5. Data analysis

The sampling volume was calculated from local flow velocities in the net (ADCP data) multiplied with the net area (2/3 × 0.5 m^2 at the surface and 0.5 m^2 at

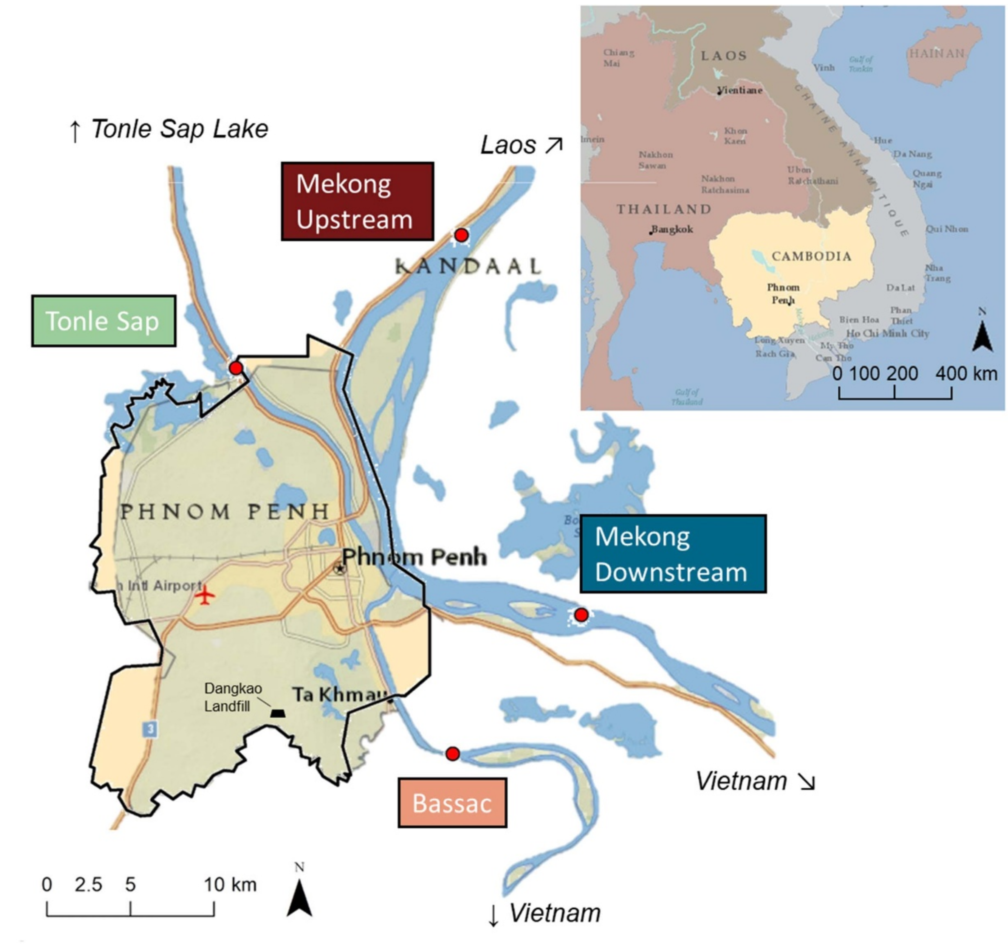


Figure 1. Overview map of the study area, including monitoring sites and landfill location in Phnom Penh, Cambodia.

Table 1. Cross-section characteristics at the sampling sites (ADCP measurements from August to September 2019).

No.	Site	Mean discharge ($m^3\ s^{-1}$)	Mean flow velocity ($m\ s^{-1}$)	Mean depth (m)	Maximum depth (m)	Width (m)
1	Mekong Upstream	39 365	1.20	17	29	823
2	Mekong Downstream	24 262	1.11	19	30	1341
3	Tonle Sap	6946	1.05	15	19	465
4	Bassac	3903	1.07	10	15	367

the subsurface) and sampling duration. Plastic concentrations are the quotient of plastic mass or count and sampling volume, and were determined both by sample and as the volume-averaged of all sample positions in the cross-section. Plastic loads were estimated based on cross-section concentrations and the ADCP river discharge portion from surface to sampling depths (12 or 8 m). Total annual plastic loads at each site were calculated as the daily plastic loads in the cross-section (average from both sampling campaigns) multiplied by the days of positive flow into the Mekong per year (365 days for the Mekong and Bassac sites and 182.5 days for the Tonle Sap due to its flow-reversal). For details, see extended methods in the supplementary material.

Parameters used for data analysis included count concentration ($\# \cdot m^{-3}$), mass concentration ($mg\ m^{-3}$), count loads ($\# \cdot d^{-1}$), mass loads ($kg\ d^{-1}$), discharge ($m^3\ s^{-1}$), and local flow velocities ($m\ s^{-1}$). Statistical data analysis included the pairwise Wilcoxon rank test to estimate differences between sites and campaigns, and the Spearman rank test for correlations (Wilcoxon 1945, Lehmann and d'Abrera 1998) at a significance level of $p < 0.05$.

3. Results

3.1. Plastic and flow dynamics

Plastic release and transport were highly variable around Phnom Penh. The Mekong carried plastics received during its long and diverse course, but loads increased significantly within the city boundaries (figure 2). We estimated that 4.35×10^9 particles or 233 tons of plastic per day were moving from Phnom Penh towards Vietnam and the South China Sea in the wet season (3.90×10^9 particles or 218 tons in the Mekong and 4.50×10^8 particles or 15 tons in the Bassac). Around 1.92×10^9 particles or 75 tons of plastic per day were carried towards the Tonle Sap lake.

The Mekong's discharge is redistributed within Phnom Penh into the Tonle Sap and the Bassac. The Mekong's discharge decreased by around 15 000 $m^3\ s^{-1}$ from *Upstream* to the *Downstream* site, possibly due to documented water losses to the floodplain (Kummu *et al* 2014). Cross-section concentrations were higher at all three outflow sites, except for *Bassac* during the first campaign. The sample concentrations at *Mekong Downstream* and *Tonle Sap* were significantly higher than those at *Mekong Upstream* and *Bassac* ($p < 0.05$). In sum, the three outflowing rivers together carried much higher plastic loads than upstream from the city.

From the first to the second sampling campaign, flow volume at *Mekong Upstream* increased by 67%, within less than two weeks. The additional flow volume reduced plastic concentrations in both Mekong and Tonle Sap. The higher flows mobilized additional plastic loads at *Mekong Downstream*, while at *Tonle Sap* those flow changes had little impact on loads. The smaller *Bassac* was most affected by the change in flows, as more plastics mobilized, increasing concentrations and loads, especially in terms of mass.

3.2. Plastic budget at Phnom Penh

Mekong Upstream carried a mean plastic load of 3.23×10^9 # $\cdot d^{-1}$ or 1.04×10^5 kg d^{-1}. The sum of loads leaving Phnom Penh through the three distributaries was 6.28×10^9 # $\cdot d^{-1}$ or 3.07×10^5 kg d^{-1} (average of both campaigns), there was more than a two-fold increase in plastics mass loads in the Mekong. These numbers suggest that in average, 3.05×10^9 # $\cdot d^{-1}$ or 2.03×10^5 kg d^{-1} of plastic entered the river confluence between sampling locations (figure 3). These loads translate to approximately 89 g d^{-1} of plastic waste released into the rivers per capita (approximately 42% of what is produced; see table S7 in supplementary materials for calculations). Count concentrations increased by 153%–292%, resulting in 151%–261% higher count loads. Mass concentrations increased by 126%–2242%, causing a 151%–2296% increase in mass loads. The difference in transport estimates between both campaigns demonstrates the high variability in a large river system like the Mekong, but also its immense transport potential. The Tonle Sap received high count loads (31%) and elevated mass loads (24%) in relation to its discharge (20%) portion. Conversely, the Bassac received 11% of the discharge but only 7% and 5% of the plastic loads.

When translating the wet season daily loads into total annual mass loads, our data suggest that the Mekong carries upstream of Phnom Penh an average of 3.81×10^4 tons yr^{-1} and downstream 7.94×10^4 tons yr^{-1}. The Tonle Sap receives 1.36×10^4 tons yr^{-1} (calculated for the six months of wet season). Lastly, we estimate annual mass loads in the Bassac to be 5.56×10^3 tons yr^{-1}.

3.3. Cross-sectional distributions of plastic concentrations

Plastic concentrations varied within each of the four cross-sections. Across the surface, there was a fluctuation of three to four orders of magnitude in mass concentration; plastic mass accumulated within the channel section and on the left-bank side (table S6 in supplementary material). Surface counts of plastics were negatively correlated to flow velocities ($p < 0.05$) and were highest near the shore in the Mekong and in the main channel in the Tonle Sap and Bassac.

In terms of mass, most plastic was floating (99.6%). Across depths, surface samples had three to five orders of magnitude higher mass concentrations than most sub-surface samples (figure 4). Mass concentrations were negatively correlated with sampling depth ($p < 0.05$). The count concentrations indicate that a considerable amount of plastic particles were transported downwards. Despite the pre-dominance of plastics at the surface and the overall decline over the sample range of 12 m, plastics were clearly present throughout the water column.

3.4. Plastic characteristics

Among the 482 particles analyzed by Raman spectroscopy, all except one were identified as polymers of six different categories (figure 5). The vast majority were polypropylene (PP; 69%) and polyethylene (PE; 12%). Polystyrene (PS) and polyamide/nylon were encountered in small fractions (4% each). The spectra of a large fraction of particles (11%) were identified to contain dyes (Hostasol Green G-K and Phthalocyanine Blue) commonly used in polymers and paints. 'Other' polymers include polyethylene terephthalate and PP/PE blends, each below 1%. The PP fraction was highest at *Mekong Downstream* (78%) and lowest at *Bassac* (55%). In the sub-samples of *Mekong Downstream* and *Bassac* no PS was encountered, and PE was less present (6% and 7%) than at *Mekong Upstream* and *Tonle Sap* (20% and 25%).

In terms of quantity, 65% of the 41 064 particles collected belonged to the smaller microplastics (smaller than 1 mm), 29% were larger microplastics

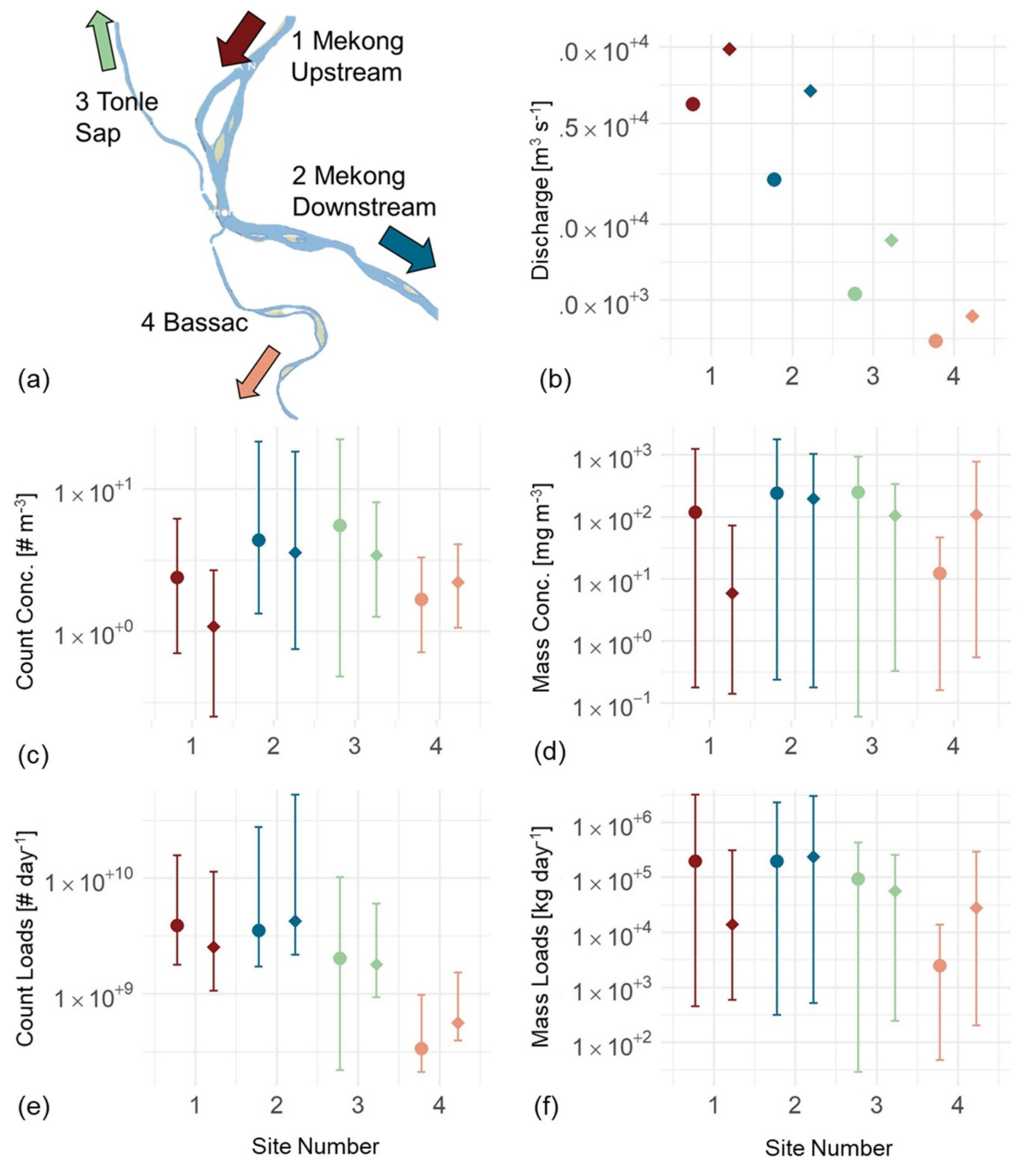


Figure 2. Overview of field results by site: (a) site reference map, (b) river discharge ($m^3\ s^{-1}$), (c) plastic count concentrations ($\# \cdot m^{-3}$), (d) plastic mass concentrations ($mg\ m^{-3}$), (e) plastic count loads ($\# \cdot d^{-1}$), and (f) plastic mass loads ($kg\ d^{-1}$). *Y*-axes r in logarithmic scale (range varies from frame to frame). The circle indicates the first and the diamond shape the second sampling campaign. Error bars indicate the minimum and maximum range based on the lowest and highest plastic count or mass from each sampling event. The map at the top left displays site locations/numbers and flow direction. See tables S2 and S3 for detailed results by sample and campaign.

(between 1 and 5 mm), and 6% macroplastics (larger than 5 mm; figure 5). These size fractions were not significantly different between samples at different positions. *Mekong Upstream* carried less large microplastics than the other sites and *Tonle Sap* had a lower fraction of macroplastics in comparison with the Mekong sites ($p < 0.05$).

4. Discussion

4.1. The role of Phnom Penh in plastic pollution

The city of Phnom Penh substantially contributes to plastic loads in the Mekong and pollution reaching the delta in Vietnam and the South China Sea. Urban areas are centers of plastic pollution and release to rivers (Yonkos *et al* 2014, Mani *et al* 2016) and Cambodia's capital is, with over 2 million people, the largest city along the course of the Mekong River. Phnom Penh generated about 5.83×10^2 tons d^{-1} of plastic waste in 2015 (Cambodian Ministry of Environment 2019) from which 4.86×10^2 tons d^{-1} were collected (21.13%, see table S7 in supplementary materials for calculations). Based on our 2019 field data and this 2015 waste generation data, 42% of the plastic waste generated in the city may be entering the Mekong River during wet season

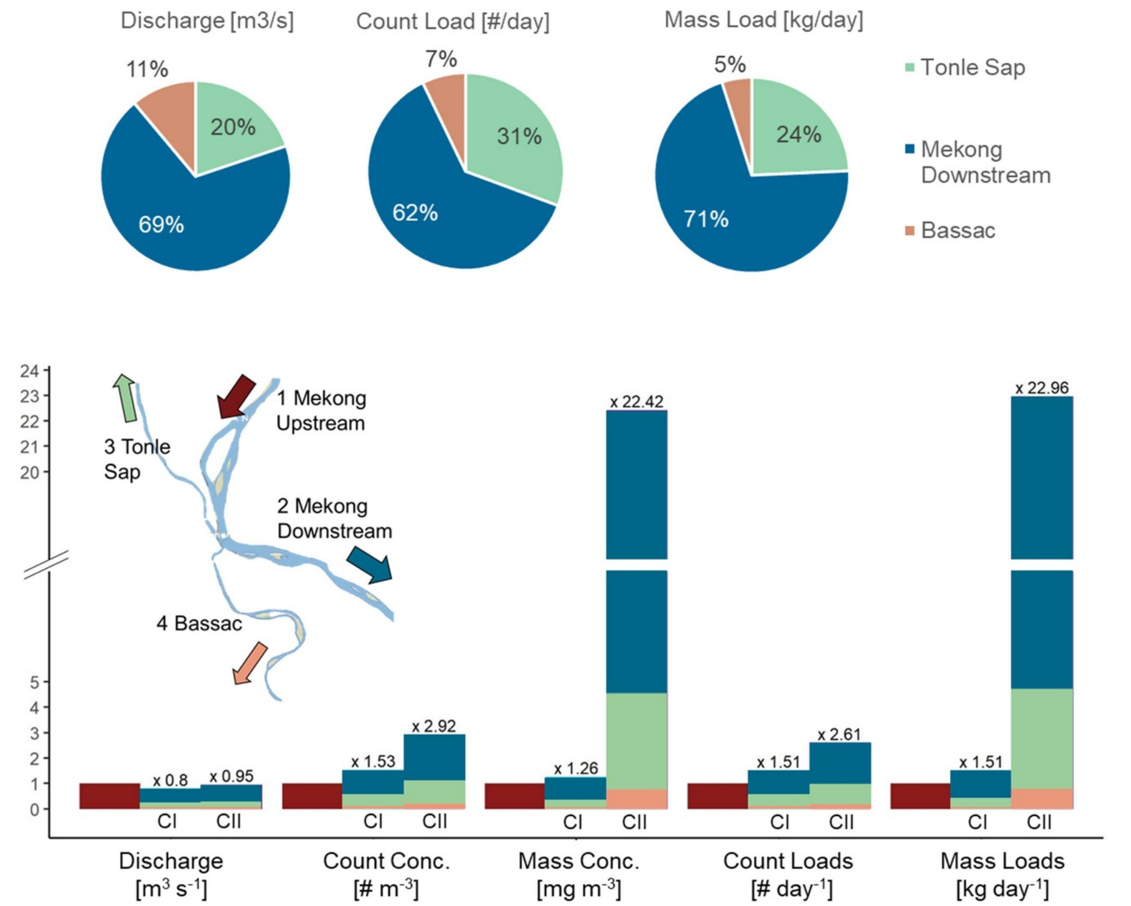


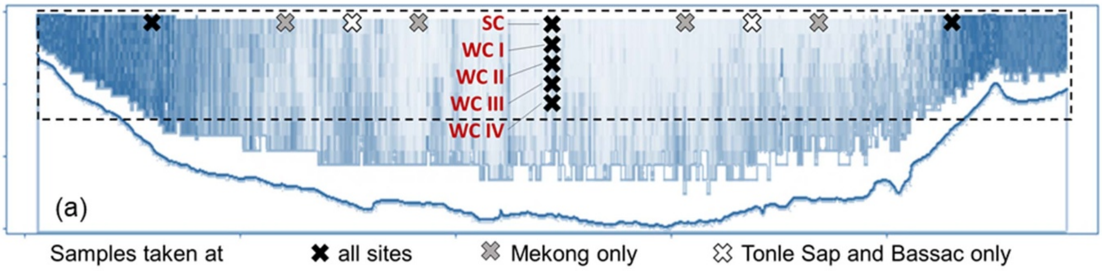
Figure 3. Ratio of discharge and plastic quantities entering and leaving Phnom Penh. The dark red bar is set as 1 and refers to the inflows of water and plastics at the *Mekong Upstream* site (see sketch). The blue-, green-, and salmon-colored bars represent the sum of outflows of water and plastics from the city at the first and second field campaign (CI and CII). The color portions indicate the approximate contribution of the three sites *Mekong Downstream, Tonle Sap*, and *Bassac.*

(2.03×10^2 tons d^{-1}). In the four year period between the two datasets, plastic waste generation and plastic collection have likely increased, factors which could affect the accuracy of this statement.

The Chaktomuk confluence connects the Mekong to the Tonle Sap, home to one of the world's largest freshwater fisheries and a system already under large pressure due to hydropower, climate change, and unsustainable fishing practices (Arias *et al* 2014, Ngor *et al* 2018, Arias *et al* 2019). The accumulation of plastics adds another physical and chemical burden on fish and other aquatic organisms (Wright and Kelly 2017) and ultimately the people living off aquatic ecosystems (van Emmerik and Schwarz 2020). At an increase of 4%–6% per year, Finnegan and Gouramanis (2021) estimated that a total of 500 000 tons of plastic will enter the Tonle Sap basin from 2020 to 2030 under a Business-as-usual scenario during the wet season flooding, with the Phnom Penh catchment contributing 80 000 tons. At a 4% annual increase, our field data suggests over 200 000 tons of plastic would be carried with the Tonle Sap river alone between 2019 and 2030. The risks associated with plastic pollution are often underestimated, especially in countries whose inhabitants face many challenges meeting their basic needs (Blettler *et al* 2018, Chowdhury *et al* 2021). Plastics, however, are known to bioaccumulate and travel through the food chain (Su *et al* 2018, Cera *et al* 2020, Sarijan *et al* 2020), and to have negative consequences for biodiversity and ecosystem services in freshwater environments (Azevedo-Santos *et al* 2021). The continuous pollution of their water bodies and their largest source of food and livelihood—The Tonle Sap—with plastics places even greater risks and challenges on the Cambodian people, flora and fauna. The extent of plastic accumulation and exchange in the Tonle Sap system, as well as its negative impact on ecosystem and human health are important subjects for future studies with plastic pollution in this important system.

4.2. Plastic loads and characteristics

The cross-section average concentrations in the Mekong were 1.74 # $\cdot m^{-3}$ or 62.62 mg m^{-3} upstream, and 3.96 # $\cdot m^{-3}$ or 220.95 mg m^{-3} downstream of Phnom Penh. The average of the surface concentrations was 2.59 $\pm$ 0.44 # $\cdot m^{-3}$ or 131.26 $\pm$ 89.42 mg m^{-3} at *Mekong Upstream*, and 8.07 $\pm$ 1.64 # $\cdot m^{-3}$ or 431.07 $\pm$ 140.41 mg m^{-3} at



(b)	Mekong Upstream		Mekong Downstream		Tonle Sap		Bassac	
SC	312.6	1.0	1.9	1039.0	251.0	220.2	46.8	75.8
WC I	0.5	0.3	0.9	0.2	6.7	2.7	0.3	1.67
WC II	0.4	0.1	0.5	0.2	0.8	1.2	0.3	10.2
WC III	0.2	0.3	0.3	0.8	0.1	0.4	0.2	0.8
WC IV	1.0	0.1	0.2	0.4	0.1	0.3	0.2	1.2

(c)	Mekong Upstream		Mekong Downstream		Tonle Sap		Bassac	
SC	2.1	1.6	1.42	3.8	3.1	8.1	3.3	3.0
WC I	2.1	0.5	2.40	1.3	2.7	2.1	1.6	1.2
WC II	0.7	0.5	2.59	0.8	1.7	3.1	1.1	1.9
WC III	1.6	0.4	1.49	2.0	0.5	1.5	1.5	1.1
WC IV	1.2	0.3	1.33	0.9	0.6	1.3	1.4	1.2

(d)	Mekong Upstream		Mekong Downstream		Tonle Sap		Bassac	
SC	1.79	2.36	1.33	1.96	1.21	1.8	1.20	1.55
WC I	1.28	2.10	1.18	1.74	1.16	1.6	1.09	1.39
WC II	1.71	2.07	1.06	0.85	0.95	1.4	1.05	1.26
WC III	1.50	1.62	0.91	0.61	1.11	1.7	0.90	1.41
WC IV	1.09	1.11	0.29	0.82	0.65	1.0	0.83	0.96

Figure 4. (a) Representative distribution of sampling locations through the river cross-sections. Water depth at the center were ∼27 m at *Mekong Upstream*, ∼25 m at *Mekong Downstream*, ∼18 m at *Tonle Sap*, and ∼14 m at *Bassac*. Sample depths varied by sampling event and location, please refer to table S2 in supplementary material for specific sample depths. Vertical distribution of (b) mass concentrations (mg m^{-3}), (c) plastic count concentrations (# $\cdot m^{-3}$) and (d) local velocities (m s^{-1}) at each site. The left column in sub-tables shows results from the first field campaign, and the right column shows results from the second field campaign. Conditional coloring according to magnitude (darker red with increasing concentration, darker blue with increasing velocity).

Mekong Downstream. Average surface water concentrations in the Yangtze were reported to be much higher (4137.3 # $\cdot m^{-3}$ and 805.2 mg m^{-3}) by Zhao *et al* (2014) during the wet season, and much lower (0.9 # $\cdot m^{-3}$) by Xiong *et al* (2019) during the dry season. In the Ganges, Napper *et al* (2021) found average surface water concentrations of 38 # $\cdot m^{-3}$ (pre- and post-monsoon study) and Singh *et al* (2021) reported 0.47 # $\cdot m^{-3}$ and 0.24 mg m^{-3} (dry season). PP and PE were the dominant plastics in our study, as it has been reported in many other studies in Asia (e.g. Zhang *et al* 2015, Lin *et al* 2018, Eo *et al* 2019, Xiong *et al* 2019, Liu *et al* 2020b, Ta *et al* 2020) and across the globe (Schwarz *et al* 2019). PS, typically found as the third most common polymer, was not common in our study (only 4% of particles analyzed with Raman). This is surprising, especially as expanded PS pieces were very frequently encountered in the macroplastics class. To our knowledge, water column studies have not been conducted in the world's largest rivers, and this is one of the first studies to report on plastic concentrations and polymer distributions through the water column of a major river in Asia.

4.3. Effects of the confluence

The Chaktomuk confluence at Phnom Penh is a unique hydrological feature with high exposure to plastic pollution. The redistribution of plastic loads to the three outflowing rivers was very heterogeneous and not directly related to their discharge. The plastic concentrations and plastic loads at the four sites suggest that relative to its size, the Tonle Sap

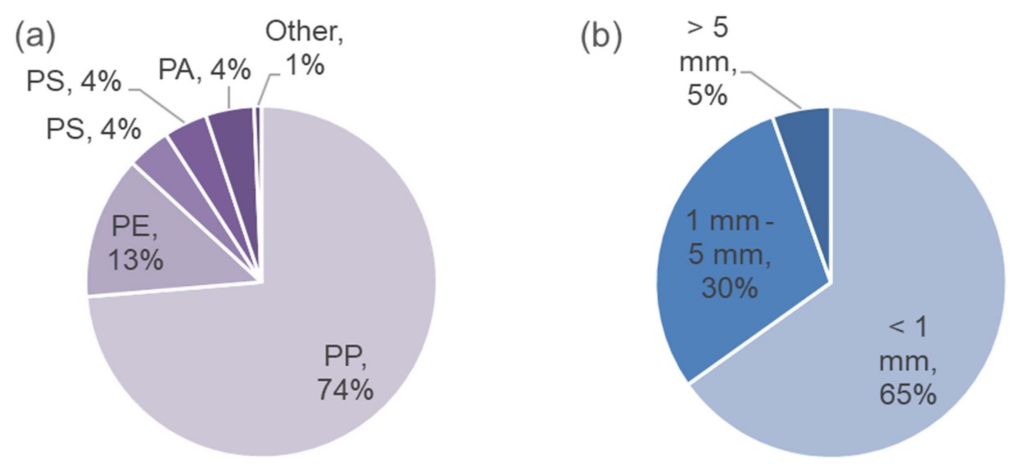


Figure 5. (a) Polymer distribution based on Raman analyzed sub-sample ($n = 481$) and (b) size distribution of total sample ($n = 41\,064$). See tables S4 and S5 in supplementary material for the underlying dataset.

received the most plastic loads from the city while Bassac received the least. During the first sampling campaign, plastic count concentrations in the Bassac were even lower than at *Mekong upstream*. The impact of water sources and spatial-variation plastic release within the city may explain these patterns, but would require further assessment. We are not aware of any other similar studies investigating the effect of river confluences or forks on plastic transport.

4.4. Effects of hydrology

Plastic fluxes are highly variable and heterogenous within river cross-sections (Haberstroh *et al* 2021a). Results of a comparative study of 24 waterways in Asia and Europe suggest that there are different distributions of floating macroplastics across the river span (van Calcar and van Emmerik 2019) and microplastics have been shown to vary strongly even between two nets deployed next to each other (Liedermann *et al* 2018). As typically observed in rivers, most of the plastic mass was concentrated at the surface and much of it transported with the bulk flow of the river. However, additional quantities may be stored temporarily within or around Phnom Penh. Plastic distribution patterns on the surface depend on site-specific environmental and human factors controlling the timescale of downstream transport or retention in the river (Liro *et al* 2020, Haberstroh *et al* 2021b). In the outskirts of Phnom Penh, many communities are located along the river. Docks and floating houses provide spatial features that likely slow down near-shore flows, and large accumulations of plastics were—anecdotally—observed around river communities during the field visits.

Our cross-section data indicates accumulation in the slow-flow sections as well as movement downwards into the lower water column of the rivers. Plastic loads in the Mekong could be, therefore, even higher than reported here, as loads in the bottom water column were not included in this study. Findings of previous studies in shallower systems suggest that near-bed plastics may be an important fraction of the total river load at certain times of the year (Morritt *et al* 2014, Haberstroh *et al* 2021a). However, near-bed transport and contribution in deep rivers has not been studied. Plastic retention is known to be favored by river geomorphology, hydrology, and artificial or natural barriers (Klein *et al* 2015, Naidoo *et al* 2015, Mani *et al* 2016) and urban rivers are suspected to contain accumulation zones of (large) plastics around cities (Xiong *et al* 2019, Weideman *et al* 2020). It is likely that plastics released at Phnom Penh may be retained within the city or along the river course; plastics may not immediately be transported to the ocean but provide a source of (micro)plastics to be slowly released over many years (Weideman *et al* 2020). Flood-induced remobilization of plastic from riverbanks, riparian vegetation, and floodplains likely drive the dynamics of river plastic transport around Phnom Penh and in the Lower Mekong (Liro *et al* 2020, Roebroek *et al* 2020).

We noticed a decrease of plastic mass concentration from the first to the second sampling campaign at *Mekong Upstream* but a large increase at *Mekong Downstream* at the same location within the river cross-section (surface center). It appears that upstream of Phnom Penh the increased flows had a diluting effect, while within the city increased amounts of plastic mass were added into the system, likely flushed in with the stormwater runoff. Storm events have led to both dilution and intensification of plastic pollution in urban rivers and increase dynamics of plastic loads (Cheung *et al* 2019, Haberstroh *et al* 2021b).

4.5. Comparison with current modeling efforts

When compared to four global and one local model of river plastic loads, the results of our field study indicate much larger annual mass loads (figure 6). Four

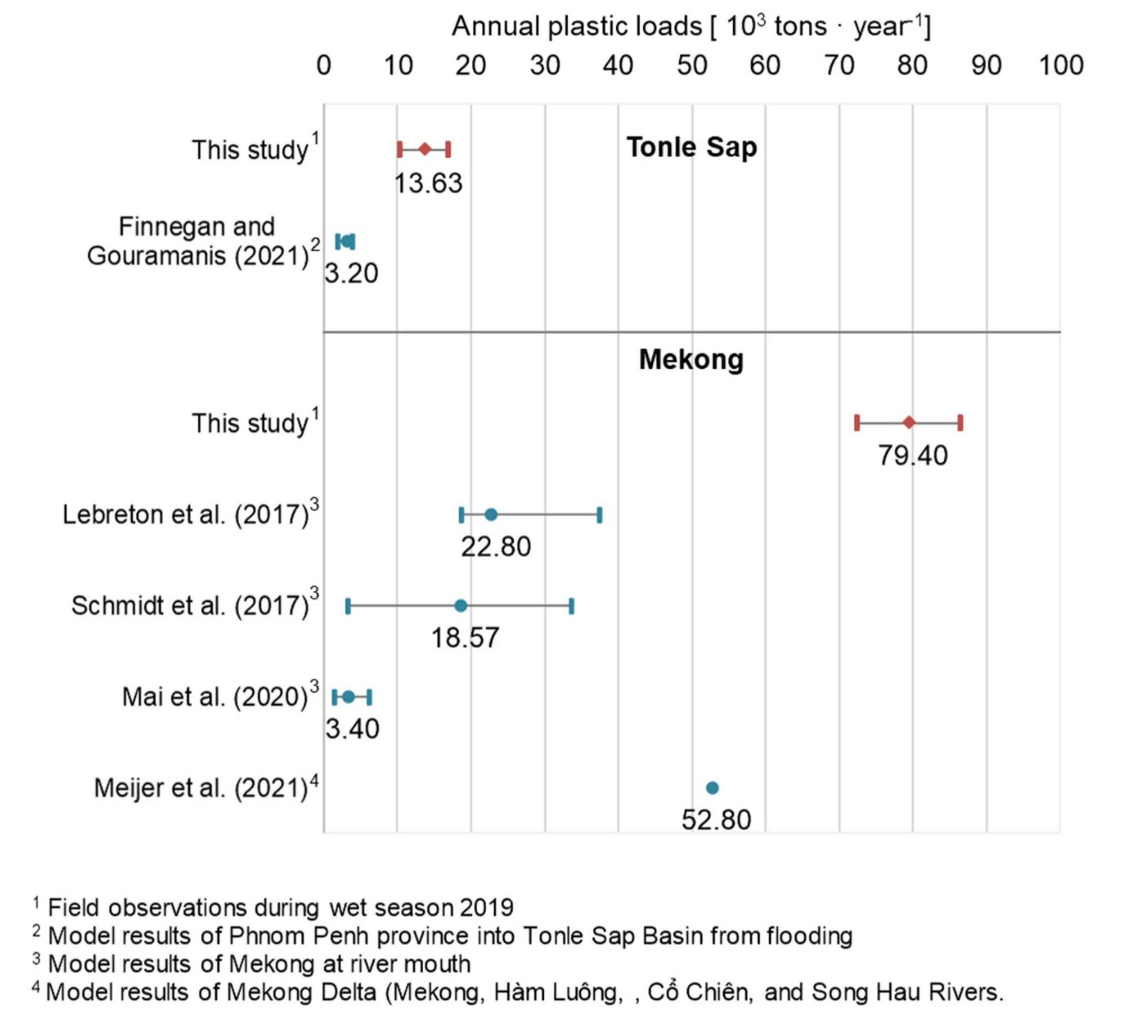


Figure 6. Annual plastic loads (tons yr^{-1}) in Mekong and Tonle Sap River compared to models estimates. The diamond and circle and respective colors indicate mean values (this study and Schmidt *et al* 2017) and medium estimates (Lebreton *et al* 2017, Mai *et al* 2020, Finnegan and Gouramanis 2021, Meijer *et al* 2021) and the error bars the minimum and maximum range.

of the models are regression models using Mismanaged Plastic Waste or Human Development Index as a key predictor and supported by other parameters such as population density, discharge, runoff, and solid waste generation (Lebreton *et al* 2017, Schmidt *et al* 2017, Mai *et al* 2020, Finnegan and Gouramanis 2021). The most recent global study presents a probabilistic distributed model for macroplastics that derived the probability of plastic transport from land to river and from river to the sea from geographical indicators (Meijer *et al* 2021). The plastic loads we measured passed Phnom Penh at *Mekong Downstream* during wet season (7.24–8.63 $\times$ 10^4 tons yr^{-1}) are much higher than any of the model results. In fact, they double the highest estimates from Lebreton *et al* (2017) and Schmidt *et al* (2017). Despite their improved regression results in comparison with its predecessors, the model by Mai *et al* (2020) underestimates our mass load measurements by one order of magnitude. For the Mekong Delta, the probabilistic model of Meijer *et al* (2021) provides the lowest estimates for plastic loads of all models. The sum of plastic loads from Mekong, Hàm Luông, Cổ Chiên, and Song Hau at discharge into the sea are 1.6% of our measurements at *Mekong Downstream*.

We also compared our field estimates with modeling results from Finnegan and Gouramanis (2021) for the Tonle Sap basin between 2000 and 2030. For our sampling year (2019), the model suggests a contribution of 2063–3987 tons from the Phnom Penh province (16% of the entire catchment). This contribution is much lower than our estimates of transport into the Tonle Sap lake (10 309–16 942 tons yr^{-1}) during the wet season. In short, this comparison suggests that not only there is a quite a bit of discrepancy among model estimates of plastic waste export from the Mekong, but also that all published models greatly underestimate our field measurements.

Collected during the wet season (discharge of 24 262 m^3 s^{-1}), our data could represent a high estimate of annual plastic loads, assuming that mass loads increase with flow. This assumption, as our data and observations in other lowland, concentration-limited rivers indicate, may not be the case (Haberstroh *et al* 2021b). Furthermore, we argue that loads in the lower Mekong may be equal or higher during the dry season, as the reversed flows of the Tonle Sap river likely carry plastics from the Tonle Sap basin and surrounding communities, adding another source of plastic pollution to the Mekong (Finnegan and Gouramanis 2021). Overall, the Mekong and other large rivers play an important role on global plastic pollution. Therefore, monitoring needs to be prioritized to challenge and improve models and to facilitate management and intervention strategies. As the number of field data collections grows in the world's largest and most polluted rivers, a field-based ranking can emerge to validate or correct model predictions of plastic loads.

5. Conclusion

This study investigated plastic transport in the Mekong, a major river and key region in global plastic pollution, with potential to release large quantities of plastics to the ocean and sensitive freshwater ecosystems. Further, this study determined micro and macro plastic pollution from the largest city along the Mekong (Phnom Penh), as well as plastic transport through a unique river confluence. During the peak of the Mekong's wet season, 42% of the plastic waste produced in the city was released into the river system towards both the South China Sea and the Tonle Sap lake, contributing significantly to marine plastic pollution and putting a freshwater ecosystem that is critical for Cambodia's livelihoods and biodiversity—the Tonle Sap—at risk. Near-surface transport dominated plastic loads in the river cross-sections, especially in terms of mass; yet, mixing was observed well down the water column for all three distributaries, suggesting that significant plastic quantities may be retained in the riverbed as well. Additional field studies during other seasons would provide insight into annual variability and could explore the changing dynamics during the Tonle Sap flow reversal. Furthermore, investigating the retention and mobilization of plastics in and close to the bed of deep rivers remains a worthy challenge for future studies. This study provided the first field-based estimates of Phnom Penh's and Mekong's plastic pollution, which is an important benchmark dataset to improve models and guide waste management.

Data availability statement

Most data collected during this study is provided in the Supplementary Materials. Additional information can be provided on reasonable request.

The data that support the findings of this study are available upon reasonable request from the authors.

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