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Large variation in Mekong river plastic transport between wet and dry season

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ABSTRACT

Plastic pollution in rivers is of increased global concern. Rivers act both as pathways for land-based plastic waste into the ocean, and as plastic reservoirs for long-term retention. Reliable observations are key to designing, optimizing and evaluating strategies to prevent and reduce plastic pollution. Several measurement methods have been developed to quantify macroplastic ($>$0.5 cm) storage and transport in rivers, including visual counting from bridges, net sampling, and images-based techniques. Method harmonization is crucial to make sure data collected using different techniques remains consistent. In turn, this would allow for comparative analysis of plastic pollution within and between rivers. In this paper, we present a harmonization approach to estimate floating plastic item and mass transport from data collected using different methods. The approach allows estimating the same values based on different measurement methods and data collection protocols. We applied our approach to the Mekong-Tonlé Sap-Bassac river system around the city of Phnom Penh, Cambodia. We estimated the floating plastic item and mass transport in the wet and dry season by combining data from net sampling and visual counting. During the wet season, plastic transport in the Mekong increased with a factor of up to 170 (item transport) and 294 (mass transport) compared to the dry season. The river plastic mass balance around Phnom Penh changed considerably, which was mainly due to the flow reversal of Tonlé Sap river between the wet and dry season. Downstream of Phnom Penh, the total plastic transport was consistently higher than upstream, although less in the wet season (1.5-1.7 times) compared to the dry season (3.8-5.9 times), emphasizing the city's role as entry point of plastic pollution into the Mekong. The largest sources of uncertainty are assumed to be caused by key differences between methods, including the size ranges, extrapolation from observation point to full river width, and the contribution of submerged plastic to the total transport. Future work should focus on including data from other methods than net sampling and visual counting, and reducing the uncertainties related to combining data from different methods. Our results show that river plastic transport dynamics are highly variable over time and space, especially around confluences, bifurcations and urban areas. With our paper we aim to contribute to further harmonization of river plastic monitoring.

Keywords: macroplastic, hydrology, water quality, Cambodia, floating plastic, marine litter, microplastic

1 INTRODUCTION

Plastic pollution in aquatic environments has detrimental effects and poses severe threats on ecosystem health, and human livelihood (Borrelle et al., 2020; MacLeod et al., 2021; Villarrubia-Gómez et al., 2022). Several efforts are underway to prevent and reduce plastic pollution locally, regionally, and globally (Silva Filho and Velis, 2022; March et al., 2022). Reliable observational data on the state of plastic pollution are key to quantify and understand plastic sources, sinks, and transport dynamics. Furthermore, observational evidence is required to make effective policy, and assess the efficacy of any prevention and reduction measures (Edelson et al., 2021; Wendt-Potthoff et al., 2020).

Rivers are considered as main pathways for land-based plastic pollution into the ocean (Meijer et al., 2021; González-Fernández et al., 2021). However, most mismanaged plastic waste never makes it into the marine environment, and accumulates in and around rivers for long time periods (Weiss et al., 2021; van Emmerik et al., 2022c). Yet, river plastic monitoring is still very sporadic. For most rivers around the world, observational data has limited spatial and temporal coverage, or is not available at all (Meijer et al., 2021; Lebreton et al., 2022). Additional challenges are caused by the use of different measurement methods, resulting in variation in the units, environmental compartments included, or calculated variables. Available data are, therefore, often not directly comparable (van Emmerik et al., in review). Recent efforts have started to harmonize river plastic monitoring methods and strategies. The harmonization efforts to date have mainly focused on providing guidelines for the design of new monitoring strategies (González-Fernández and Hanke, 2017; Wendt-Potthoff et al., 2020). However, method harmonization may also offer opportunities to combine existing data collected through different methods.

In this paper, we present a simple harmonization approach that allows to estimate floating river plastic transport using data collected through different techniques. We applied the method to the Mekong river around Phnom Penh, Cambodia, where it forms a complex river network with the Tonlé Sap and Bassac rivers (Haberstroh et al., 2021a). The available data were collected through net sampling from boats in the wet season of 2019, and through visual counting from bridges in the dry season of 2022 (Haberstroh et al., 2021a; van Emmerik et al., in review). We use the available raw data to estimate the total amount of floating plastic items and their mass transport. The results shed new light on the spatial and temporal variability of plastic transport dynamics in the Mekong.

Here, we show that both the floating item and mass plastic transport can be several orders of magnitude higher in the wet season (June-November) compared to the dry season (December-May). Furthermore, our results highlight that river plastic transport dynamics are complex, especially in in the Mekong-Tonlé Sap-Bassac system. The flow direction in the Tonle Sap reverses between the wet and dry seasons, driven by the difference in hydraulic head between Tonlé Sap Lake (Northwest of Phnom Penh) and the Mekong river (Arias et al., 2012). This reversing, in combination with the strong seasonality in river discharge, makes that the difference between plastic transport upstream and downstream of Phnom Penh changes considerably between the wet and dry season. The results emphasize the consistent role of Phnom Penh as entry point of plastic pollution. We identified uncertainties in the different transport estimates due to

Table 1. Overview of the measurement locations where the sampling was done during the wet season and the dry season.

	Coordinates	Point	Obs. points	Width	Dates	No. obs.	Duration [min]	Discharge [m^3/s]	Discharge (Kratie) [
Wet season (Net sampling)									
Mekong Up	11.730851, 104.983018	Boat	7	823	29 Aug, 9 Sep 2019	14	133.5	39,350	38,904
Mekong Down	11.534125, 105.055145	Boat	7	1341	2 Sep, 11 Sep 2019	14	141.5	24,250	38,904
Tonlé Sap	11.661339, 104.866375	Boat	5	465	28 Aug, 5 Sep 2019	10	150	6,970	N/A
Bassac	11.462558, 104.979622	Boat	5	367	4 Sep, 14 Sep 2019	10	150	3,895	N/A
Dry season (Visual counting)									
	Coordinates	Point	Obs. points	Width	Dates	No. obs.	Duration [min]	Discharge [m^3/s]	Discharge (Kratie)
Mekong Up	11.752342, 105.003625	Prek Tameak Bridge	5	610	26 Feb, 28 Feb, 1 Mar, 4 Mar 2022	162	705	N/A	2,887
Mekong Down	11.275617, 105.279131	Tsubasa Bridge	5	600	26 Feb, 28 Feb, 1 Mar, 4 Mar 2022	153	765	N/A	2,887
Tonlé Sap	11.661339, 104.866375	Prek Pnov Bridge	5	375	26 Feb, 28 Feb, 1 Mar, 4 Mar 2022	98	430	N/A	N/A
Bassac	11.530877, 104.933064	Monivong Bridge	5	500	26 Feb, 28 Feb, 1 Mar, 4 Mar 2022	144	414	N/A	N/A

the size range, extrapolation from observation width to the full river width, and omission of subsurface plastic transport. However, in the results underscore the importance of seasonality. With this paper we aim to provide a next step towards harmonization of river plastic monitoring methods. Furthermore, we demonstrate that by combining data in a harmonized way we can reveal plastic transport dynamics in complex river systems.

2 METHODS

2.1 Study area

The Mekong river is nearly 5000 km long, and its basin spans across China, Thailand, Laos, Cambodia and Vietnam. We focused on the area around Phnom Penh, the capital city of Cambodia. Here, the Mekong is joined by the Tonlé Sap river, which connects to the Tonlé Sap Lake around 100 km upstream of Phnom Penh (Fig. 1). The flow direction in the Tonlé Sap river switches during the year. During the wet season, the discharge flows from the Mekong towards Tonlé Sap Lake, and during the dry season the Tonlé Sap flows into the Mekong. The direction depends on the difference in hydraulic head between Tonlé Sap Lake and the Mekong (Arias et al., 2012; Kummu et al., 2014). Directly downstream of the Mekong-Tonlé Sap confluence, the Mekong splits into the main Mekong branch and the Bassac river, which both end in the Mekong delta. We compare data at four locations: Mekong Upstream, Mekong Downstream, Tonlé Sap and Bassac (Figure 1). The wet and dry season data at Mekong Upstream and Tonlé Sap were taken at nearly the same locations. For Bassac and Mekong Downstream, the distance between the measurement locations were 10 km and 40 km, respectively. The data used in this study was collected using net sampling, and the visual counting method. Net sampling was done in August and September, 2019 during the wet season (Haberstroh et al., 2021a). Visual counting was done in February and March, 2022, during the dry season van Emmerik et al. (in review).

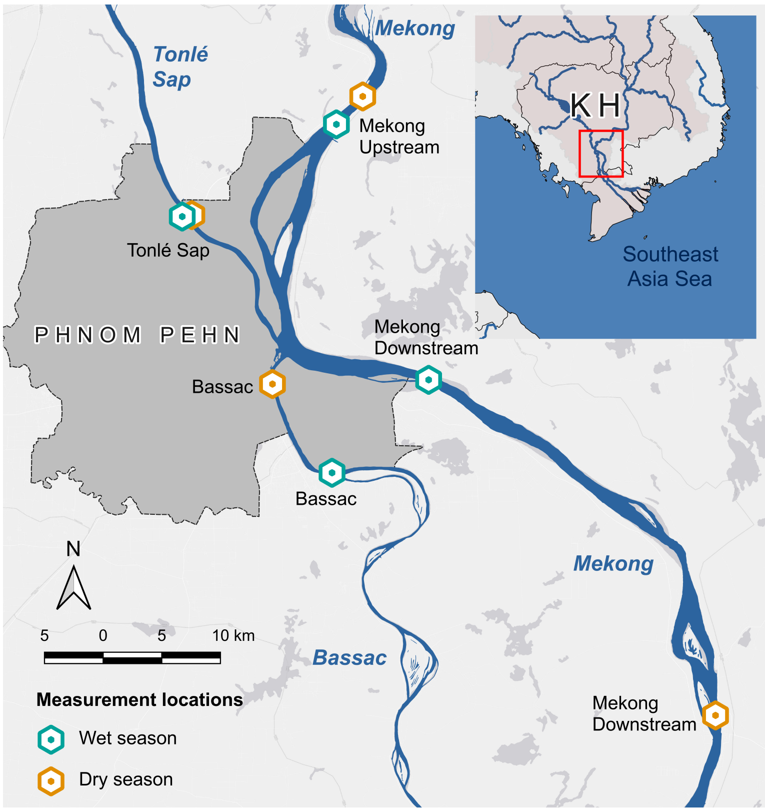

Figure 1. Overview of the study site, including the four measurement locations at Mekong Upstream, Mekong Downstream, Tonlé Sap and Bassac. Note that between the wet and dry season measurements, some locations were shifted due to method limitations.

2.2 Net sampling

We used the macroplastic data provided by Haberstroh et al. (2021a). Samples were taken at all four measurement locations on two days during the wet season in August and September, 2019. A 500 μm Neuston net with a frame of 0.5x1 m^2 was used, equipped with removable floats and weights. The surface samples were collected at five to seven points across the river with at the upper 0.2 m of the water column (Fig. 2a). The net was deployed from a semi-stationary boat, with sampling duration between 6 and 15 minutes. The collected sample was sieved and the large macroplastics (>0.5 cm) were separated manually. The remaining microplastics were processed further, but this is outside the scope of this study. Note that also subsurface plastic samples were taken, but these data are also not used in this study.

2.3 Visual counting

We used the data provided by van Emmerik et al. (in review). During the dry season floating plastic transport was measured using the visual counting method (González-Fernández and Hanke, 2017). All floating plastic items were counted from bridges for a duration ranging from two to five minutes. At all locations, five measurement points were selected, all with an observation track width of 15 meters (Fig. 2a). The counted items were classified in one of the seven polymer categories using a list of typical items that belong to each category (van Emmerik et al., 2022a); PET (polyethylene terephthalate), PO_{soft} (soft polyolefin), PO_{hard} (hard polyolefin), PS (polystyrene), ML (multilayer), EPS (expanded polystyrene) and other plastic. Each observation point was measured at least four times per day. At all locations data were collected on the same four days (26 Feb, 28 Feb, 1 Mar, and 4 Mar, 2022).

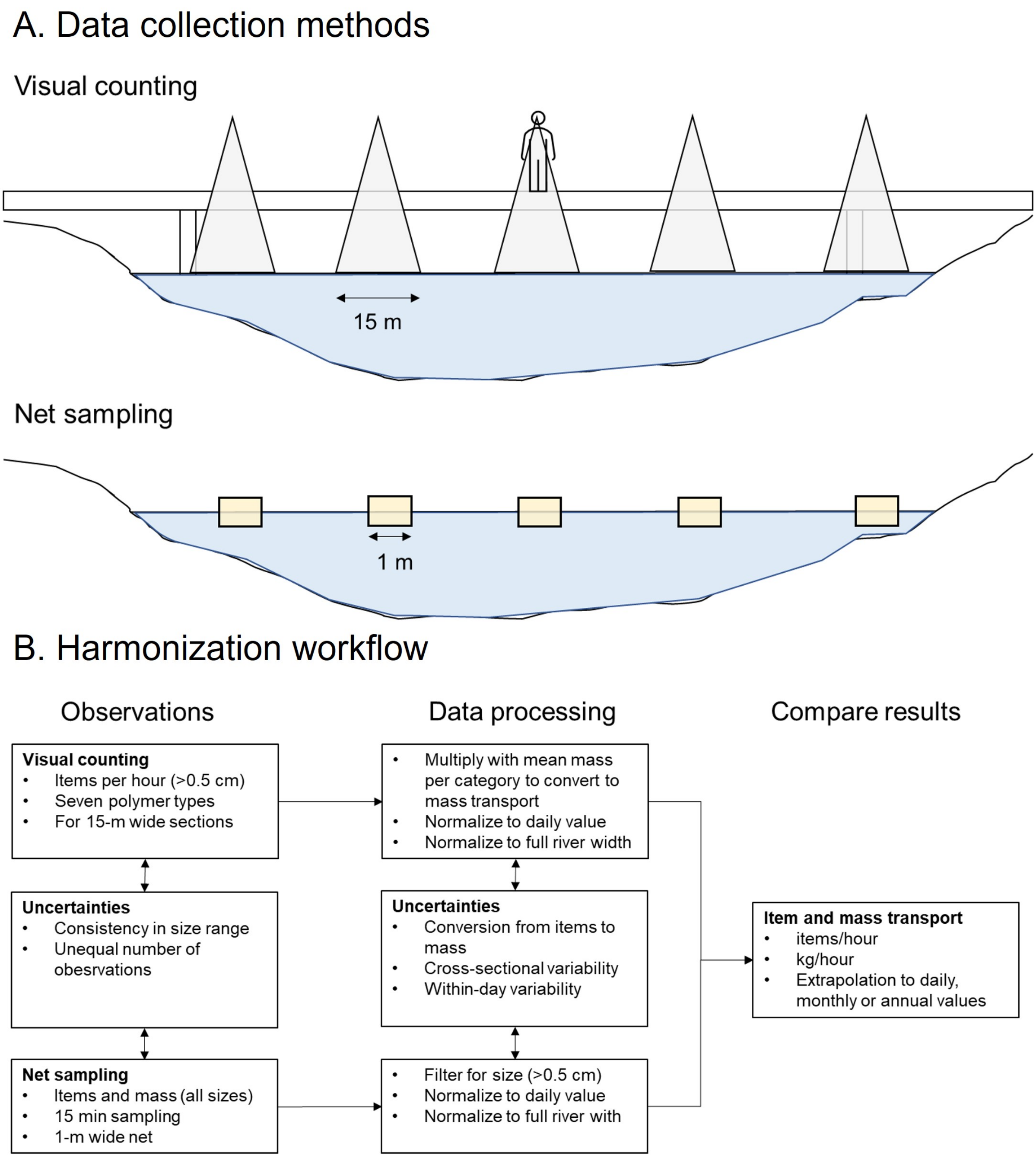

Figure 2. A. Overview of the two methods used for data collection: (1) Visual counting from bridges. This was done at five points across the river width, for which 15 m-wide segments were observed, (2) Net sampling from boats. This was done at five points across the river width using a 1 m-wide net. B. Workflow for harmonizing the raw data from two different measurement methods to calculate the floating plastic item and mass transport.

2.4 Method harmonization

To harmonize the data from the net sampling and the visual counting, we developed a workflow to calculate the same variables (item and mass transport) using similar scaling principles (Fig. 2b). The plastic item transport T_n [items/hour] and plastic mass transport M_n [kg/d] based on the net sampling were estimated using the following equations.

$$T_n = \frac{C_n}{d} \cdot t \cdot \frac{W}{b_n} \cdot R_m \tag{1}$$

$$M_n = \frac{m_n}{d} \cdot t \cdot \frac{W}{b_n} \cdot R_m \tag{2}$$

With total sampled plastic items C_n [items], the duration of the sampling d [min], the time scale of interest (e.g. 60 for hourly values, 1440 for daily values), the river width W [m], net width b_n [m], and fraction of items that are macroplastics R_m. Note that the river width is not constant over time. For our assessment, we used different river width values for the wet and dry season (Table 1). For the mass transport, we used the total sampled plastic mass m_n.

The item transport T_v based on the visual counting were estimated using the following equation:

$$T_v = \frac{C_v}{d} \cdot t \cdot \frac{W}{b_s} \tag{3}$$

With total counted plastic items C_v [items], duration d [min], and observation track width b_v.

The mass transport was calculated using three different methods (van Emmerik et al., 2022a): using the mean item mass for each polymer category ($M_{v,1}$), using the overall mean item mass ($M_{v,2}$), and using the overall median item mass ($M_{v,3}$). We used the following equations:

$$M_{v,1} = \sum_{j=1}^{j=7} \frac{C_v, j \cdot \bar{m}_j}{d} \cdot t \cdot \frac{W}{b_v} \tag{4}$$

$$M_{v,2} = \frac{C}{d} \cdot \bar{m} \cdot t \cdot \frac{W}{b_v} \tag{5}$$

$$M_{v,3} = \frac{C}{d} \cdot \tilde{m} \cdot t \cdot \frac{W}{b_v} \tag{6}$$

With total counted items C_v per category j, mean mass $\bar{m}$ per polymer category j, mean mass per plastic item $\bar{m}$, and median mass per plastic item $\tilde{m}$. Note that $M_{v,1}$ uses the mean mass per polymer category for the seven-class categorization, $M_{v,2}$ uses the general mean mass per plastic item, and $M_{v,3}$ uses the general median mass per plastic item. Note that none of these methods require flow velocity data, which is crucial for the net sampling-based estimates. As no local data were available, we used the item-mass statistics from de Lange et al. (2023).

3 RESULTS AND DISCUSSION

3.1 Floating item and mass transport

During the wet season, the floating plastic transport in the main Mekong branch increased from $3.3 \cdot 10^6$ items/day upstream to $7.3 \cdot 10^6$ items/day downstream (Fig. 3a). The transport in the Bassac was $0.9 \cdot 10^6$ items/day, and in the Tonlé Sap $4.1 \cdot 10^6$ items/day were flowing towards the Lake. In the dry season, the floating transport increased from $1.9 \cdot 10^4$ to $4.8 \cdot 10^4$ items/day in the Mekong (Fig. 3b). In the Tonlé Sap, the transport was $4.3 \cdot 10^4$ items/day towards the Mekong. The item transport in the Bassac was $4.6 \cdot 10^4$ items/day.

Mass transport increased from $1.7 \cdot 10^3$ to $6.8 \cdot 10^3$ kg/day between the upstream and downstream point along the Mekong (Fig. 3c). The transport in the Bassac and Tonlé Sap were $0.5 \cdot 10^3$ and $2.8 \cdot 10^3$ kg/day, respectively. We calculated the floating mass transport in the dry season using three methods, which range over one order of magnitude (Fig. 3d). In the Mekong main branch, the mass transport increased from $9.2 \cdot 10^0$ to $1.9 \cdot 10^2$ kg/day upstream to $2.3 \cdot 10^1$ to $5.3 \cdot 10^2$ kg/day downstream. The transport in the Tonlé Sap and Bassac are estimated at $2.1 \cdot 10^1$-$0.4 \cdot 10^3$ and $2.2 \cdot 10^1$-$0.5 \cdot 10^3$ kg/day, respectively.

3.2 Difference between wet and dry season

For the item transport, we found a 20 to 170 time increase between the wet and dry season. The latest increase was found in the main Mekong branch (170 and 153 for upstream and downstream, respectively). Transport in the Tonlé Sap river was 95 times larger in the wet season, but even more important is the flow reversal. During the dry season, the Tonlé Sap flows into the Mekong. The smallest increase was found in the Bassac (20 times).

For the mass transport, the difference between wet and dry largely depends on the chosen calculation method for the visual estimates. The estimates using the mean item mass ($M_{v,1}$ and $M_{v,2}$), the multiplication factors are one order of magnitude lower than for the estimates using the median item mass ($M_{v,3}$). The largest increase (based on $M_{v,1}$ and $M_{v,2}$) was again found for the upstream (9-15 times) and downstream (13-23 times) Mekong locations. Tonlé Sap and Bassac increased with a factor 7 to 11, and 1 to 2, respectively. The difference based on $M_{v,3}$, the amplification was 186 (upstream) and 294 (downstream) for the Mekong, 138 for Tonlé Sap, and 23 for the Bassac.

The discharge in Kratie, at the Cambodian-Laotian border, was 2,887 m^3/s in the dry season (2022) and 38,904 m^3/s in the wet season (2019). The average measured discharge during the wet season at the Mekong Up and Mekong down locations was 39,350 m^3/s and 24,250 m^3/s, respectively. Discharge increased with a factor 13.5, which is of similar magnitude as the lower amplification factor of plastic mass transport, but much lower than the amplification factor for the item transport. In other rivers it was found that plastic transport generally increases disproportionally to the increase in discharge. In the Seine, plastic transport increased with a factor ten when discharge increased only a factor three (van Calcar and van Emmerik, 2019). A recent study in the Meuse found a power law relation between discharge and plastic transport, suggesting a non-linear response of plastic transport to discharge (van Emmerik et al., 2022b). The disproportional increase of plastic transport to discharge is generally explained by additional mobilization of plastic towards the river, and remobilization of accumulated plastics on the riverbanks and floodplain due to increased water level and flow velocities.

3.3 Changes in the mass balance

During the wet season the Tonlé Sap river flows from the main Mekong branch towards the Tonlé Sap Lake, with an estimated plastic transport of $2.8 \cdot 10^3$ kg/day. In the dry season the flow reverses, resulting in $2.1 \cdot 10^1$-$4.3 \cdot 10^2$ kg/day. Given that the inflow from the Mekong into the Tonlé Sap during the wet season is 7 to 138 times higher that the backflow during the dry season, the Mekong may be a main source of plastic pollution found in the Tonlé Sap river and Lake. The overall mass balance also changes considerably, and specifically the difference between the total upstream and downstream transport. In the wet season, the total downstream transport (Tonlé Sap, Bassac and Mekong Downstream) is 3.8 (items) to 5.9 (mass) times larger than the upstream transport (Mekong Upstream). The the dry season, the increase from upstream

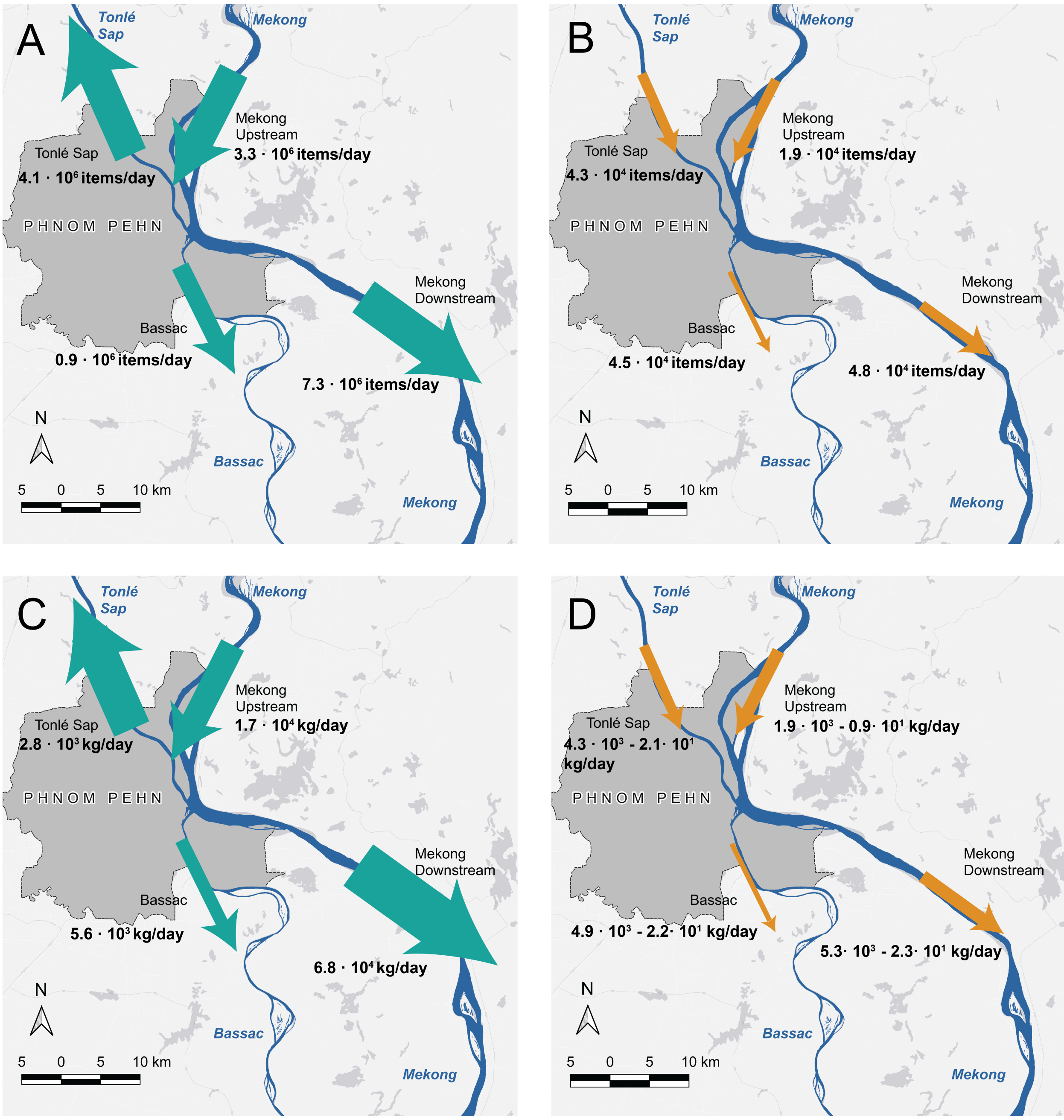

Figure 3. Item and mass transport for the Mekong, Tonlé Sap and Bassac measured in the wet and the dry season. A. Item transport measured in the wet season (Aug-Sep 2019). B. Item transport measured in the dry season (Mar 2022). C. Mass transport measured in the wet season (Aug-Sep 2019). D. Mass transport measured in the dry season (March 2022). Note that the range in the dry season mass transport estimates is due to using different calculation methods (see Methods). Also note the reverse of the plastic transport direction in the Tonlé Sap river between the wet and dry seasons.

(Mekong Up and Tonlé Sap) to downstream (Bassac and Mekong Down) is only a factor 1.5 (item) to 1.5-1.7 (mass). The mass balance suggests that during the wet season, even more plastic enters the river system from Phnom Penh (Haberstroh et al., 2021a). Also in other urban areas connected to natural river it has been found that during periods of increased rainfall and discharge, more plastic are mobilized and transported into rivers (Treilles et al., 2022; Tasseron et al., 2022). To better quantify and understand sources of riverine plastic, also the seasonality of entry processes should be considered.

3.4 Uncertainties and limitations

In this paper we present a first harmonization effort that combines macroplastic observations collected through different methods, in different time periods. Although the data collection has been relatively well documented, several assumptions may have introduced sources of uncertainty in the item and mass transport estimates. First, we assumed a similar size range (>0.5 cm) for the observed and sampled items. The samples collected with net sampling were sieved, and therefore the minimum detected size is relatively certain. For visual counting, it is generally assumed that items larger than 0.5 cm can be seen from bridges up to 10 m tall. However, for taller bridges the minimum detectable item size may increase to 1 to 5 cm for bridges up to 30 m (Castro-Jiménez et al., 2019; González-Fernández et al., 2021; van Emmerik et al., 2022a). The item size-mass distribution varies considerably between rivers. To illustrate, we compared sampled data from the Rhine, Netherlands, and Saigon, Vietnam, rivers. In the Rhine, more than 40% of the items was smaller than 5 cm. Yet, this contributed only 12% to the total mass Vriend et al. (2020). In the Saigon, only around 10% of the items was smaller than 5 cm, of which the mass was close to negligible van Emmerik et al. (2019). We acknowledge that the visual observation measurements may underestimate the abundance of items between 0.5 and 5 cm, potentially missing 10 to 40% of the item transport and up to 12% of the mass transport. However, compared to the seasonal variability of 1-2 orders of magnitude, the uncertainty is relatively low.

Second, the extrapolation to the full river width is considered more uncertain for the net sampling due to the limited sampling area. With five to seven 1-m wide sampling points, the share of the observed width ranged between 0.5 and 1.4%. Visual counting from bridges had five 15-m wide observation points, equalling 12.3 to 20.0% of the total river width. Depending on the river, location within the river, and the time, the cross-sectional distribution of floating plastic can range from uniformly distributed to heavily concentrated. For example, the Rhine showed a concentrated profile with 50% of the transport occurring within near to 20% of the width (90% in nearly 60%). Other rivers, such as the Chao Phraya and Ciliwung show a close to uniformly distributed profile (50% and 90% of transport in 50% and 90% of the width, respectively) (van Calcar and van Emmerik, 2019).

Finally, we only considered surface transport in this study. The original study by Haberstroh et al. (2021a) demonstrated that the vertical profile of plastic item and mass concentration is highly variable. During periods with the highest surface concentrations, the subsurface concentrations were relatively low (up to 2000 times). However, in some cases the highest concentrations were measured below the surface. Given a depth between 15 and 30 m in the study area (Haberstroh et al., 2021a), the subsurface transport may be considerably higher than the floating transport only. In our study we purposefully focused on floating plastic transport only. Depending on the plastic characteristics and flow regime, items may be transported closer to or further from the surface (Haberstroh et al., 2021b; Valero et al., 2022). During the dry season, relatively high portions of positively buoyant plastics were observed (PET: 9% vs 1%, (Expanded) PS: 29% vs 3%). In the wet season the majority of items were PP and PE (85% wet, vs 39% dry), which are more likely to also be found below the surface. The difference in total plastic transport between the wet and dry season may therefore be even be higher.

3.5 Outlook

In our paper we show how data collected through different methods can be combined to derive the same metrics of floating plastic transport. In the proposed harmonization workflow it is crucial to extrapolate to the river width, and to the same unit of time (hours or days). It is therefore important that the spatial extent and duration of measurements are clearly reported. For image-based techniques the temporal dimension may be challenging, as these are often done on single images taken at a certain moment in time (Geraeds et al., 2019). These observations should be complemented with either additional images, or flow velocity estimates, to convert the observations to transport per unit of time. Extrapolation from the observation width to the total river width should not be an issue with most conventional monitoring methods (e.g. net width, image footprint, observation track width), as long as the dimensions are reported. However, the river width can change over time (Table 1), and therefore needs to be measured as well.

Combining the data collected during the wet and dry season confirms the strong seasonality of plastic transport. Previous work found that plastic item transport can vary one to two orders of magnitude during the year (van Calcar and van Emmerik, 2019; Schirinzi et al., 2020; Cesarini et al., 2023). Here, we demonstrate that also the floating plastic mass transport can increase with a factor of 9 to 294 during the wet season compared to the dry season. Especially during periods of high discharge and extreme events (e.g. floods), plastic mobilization and transport are amplified. For reliable long-term monitoring and annual transport estimates, it is therefore crucial that also during such periods data is collected. Not all methods are however suitable to be applied during extreme flow conditions. During floods, large debris and debris patches can make net sampling challenging and dangerous, both from boats or bridges (van Emmerik et al., 2022b). Visual counting from bridges or image-based techniques provide a safe alternative. Our paper may provide guidance on how multiple methods can be combined for long-term measurement strategies under varying flow conditions.

Finally, the results from our paper demonstrate the complexity of river plastic transport dynamics. Within the field of plastic pollution research, rivers have often been considered as conduits for land-based plastic waste towards the ocean. The morphology, hydrology, connection to urban areas, and seasonality are just some of the factors that result in highly non-linear and discontinuous plastic transport processes (Haberstroh et al., 2021c; van Emmerik et al., 2022a). This becomes even more complex because of the diversity of plastic characteristics, including polymer type, effective buoyancy, and geometry. Increased evidence supports the hypothesis that most mismanaged plastic waste does not enter the sea, but rather accumulates in and around rivers where they may be retained for long periods of time (Tramoy et al., 2020; van Emmerik et al., 2022c). Only through improved observational capacities the appropriate data can be collected to better understand and quantify river plastic transport dynamics.

4 CONCLUSIONS

In this paper we demonstrate how floating plastic data collected through different methods can be harmonized and combined to gain new insights in river plastic transport. We used data from net sampling in the wet season, and visual counting in the dry season to estimate the plastic item and mass transport.

In all branches of the Mekong-Tonlé Sap-Bassac system the floating plastic transport increased considerably in the wet season compared to the dry season. The largest increase was found in the main Mekong branch, with 153-170 times more item transport and 9 to 294 times more mass transport. The transport in the Tonlé Sap and Bassac were up to 138 and 23 times more in the wet season, respectively. The results revealed a strong seasonal variation in plastic transport.

The mass balance of the Mekong-Tonlé Sap-Bassac system changed substantially between the seasons. During the wet season the Tonlé Sap river flows from the main Mekong towards Tonlé Sap Lake, but reverses during the dry season. The total increase in the total transport from upstream to downstream of Phnom Penh changed from a factor 1.5-1.7 (wet season) to 3.8-5.9 (dry season). The results underscore the role of Phnom Penh as potential major entry point of plastic pollution, especially during the wet season.

Further harmonization efforts should focus on reducing the uncertainties when combining data from different methods. The most important sources of uncertainty were assumed to be caused by the considered size ranges, the extrapolation from the observation points to the full river width, and omission of submerged share of total plastic transport. We recommend the development of guidelines to further align practical choices independently of the selected method, including size range, portion of the river width to be sampled, and measurement duration.

This paper shows that river plastic transport dynamics can be highly complex, especially around confluences, tributaries, and urban areas. Improved data collection is key to better understand and quantity the plastic sources, sinks, and pathways. With our paper we aim to contribute to further harmonization and development of plastic pollution monitoring strategies in aquatic systems.

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

Conceptualization: TvE, LS; Methodology: TvE, LS; Formal Analysis: TvE, LS, MA; Investigation - Data collection: TvE, LS, YV; Visualization: LS; Data curation: TvE; Writing–original draft: TvE, LS; Writing–reviewing and editing: all authors; Supervision: TvE; Project administration: TvE; Funding acquisition: TvE.

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DATA AVAILABILITY STATEMENT

The visual counting observations during the dry season are openly available through `http://doi.org/10.4121/21763220`. The net sampling data are openly available through `http://doi.org/10.1088/1748-9326/ac2198`.

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