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Riverine plastic emission from Jakarta into the ocean

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Abstract

Plastic pollution in aquatic environments is an increasing global risk. In recent years, marine plastic pollution has been studied to a great extent, and it has been hypothesized that land-based plastics are its main source. Global modeling efforts have suggested that rivers in South East Asia are in fact the main contributors to plastic transport from land to the oceans. However, due to a lack of plastic transport observations, the origin and fate of riverine plastic waste is yet unclear. Here, we present results from a first assessment of riverine macroplastic emission from rivers and canals that run through a densely populated coastal urban city. Using a combination of field measurements, empirical relations and hydraulic modeling, we provide an estimate of total riverine plastic export originating from Jakarta, Indonesia, into the ocean. Furthermore, we provide insights in its composition, and variation in time and space. We found that most macroplastics in Jakarta consists of films and foils. We estimate that 2.1×10^3 tonnes of plastic waste, is transported from land to sea annually, equaling 3% of the total annual unsoundly disposed plastic waste in the Jakarta area.

1. Introduction

Marine plastic pollution is an emerging global risk (Wilcox *et al* 2015, Conchubhair *et al* 2019), threatening marine fauna (Derraik 2002, Thompson *et al* 2004) and ecosystems (Syakti *et al* 2017, Lasut *et al* 2018). Tackling marine plastic pollution is a contemporary challenge in ocean governance (Haward 2018), especially given the uncertainties in the origin and fate of marine plastic. Land-based plastics are considered to be a main source of marine plastic pollution (Jambeck *et al* 2015), and are assumed to mainly be transported to the ocean through rivers (Lebreton *et al* 2017, Schmidt *et al* 2017).

The origin and fate of land-based plastic waste remains understudied, but riverine plastic pollution is an emerging field. In recent years, several studies have quantified plastic pollution in rivers, such as the river Seine (Gasperi *et al* 2014), the Thames (Morritt *et al* 2014), rivers in the Los Angeles area (Moore *et al* 2011) and the Saigon river (Lahens *et al* 2018, van Emmerik *et al* 2018). However, most studies tend to be biased towards European and North American rivers, as almost 70% of the riverine plastic studies have been done in high-income countries (Blettler *et al* 2018). Unfortunately, this does not match the locations where recent modeling efforts predict the largest sources of marine plastic pollution (Lebreton *et al* 2017, Lebreton and Andrady 2019). Therefore, there is a clear need for (field) studies in areas currently under-represented in the literature. Also, understanding the origin, fate and pathway of plastic waste is a prerequisite for optimal plastic collection.

Indonesia is estimated to be the second largest emitting country of riverine plastics in the world (Lebreton *et al* 2017), which is mainly due to high population densities in coastal areas, in combination with high amounts of mismanaged plastic waste (Lebreton and Andrady 2019). Indonesia is located within the Coral Triangle, which has the highest marine diversity on the planet (Tomascik *et al* 1997, Spalding *et al* 2001). In turn, this area also has the highest risk of plastic pollution to the marine environment (Lasut *et al* 2018). Recent work has demonstrated that plastic pollution found on Indonesia's beaches mainly originates from rivers (Syakti *et al* 2017). With around 10 million inhabitants Jakarta is the largest urban area in Indonesia, and is considered one of the largest sources of Indonesia's plastic marine pollution (Willoughby *et al* 1997). Yet, very little is known about the order of magnitude, spatiotemporal variation and driving mechanisms of riverine plastic transport in the Jakarta area.

The primary aim of this study was to provide a first estimation of macroplastic emission from rivers and canals that run through the city of Jakarta into the sea. Plastic flux and composition measurements were done during a two-week field assessment across five (canalized) river sections in Jakarta, using net sampling and visual counting techniques. This study was limited to plastic items of 1 cm and larger. Results from a hydraulic model were used to extrapolate the field observations to predict total annual plastic emission into the ocean. Waterways in dense urban areas such as Jakarta are under heavy anthropogenic influence, adding an extra degree of complexity in the assessment of riverine plastic transport. A second aim of this study was to demonstrate how simple measurements, empirical relations and hydrodynamic model output can be used to estimate plastic transport across time and space. The results of the study emphasize the need for additional research on similar areas around the world.

2. Methods

2.1. Study site

Located in Northwestern Java, the city of Jakarta is the capital of the Republic of Indonesia. Jakarta has a tropical monsoon climate, with a wet season running from October to May. To predict the annual plastic emission of the city, surveys were carried out at five rivers across Jakarta. These locations were selected based on the availability of safe observation points (i.e. bridges). For the estimation of the total outflow from Jakarta, the five locations with the highest predicted annual discharge were selected, based on results of a hydraulic model (see section 2.3).

2.2. Plastic surveys

Riverine plastic flux was quantified at each monitoring location through (1) visual counting and (2) sampling using bridge-mounted trawls during a two-week period in May 2018. Visual counting (González-Fernández and Hanke 2017, van Emmerik *et al* 2018) was done hourly between 9 AM and 5 PM across the whole river cross-section. At each observation point, all plastic items were counted within a 5 m section below the observation point for a duration of 1 min. From these measurements, both the variation across the river width as in time could be studied.

Single and double-layered trawls were applied from bridges to sample debris, in order to determine (1) the ratio between plastic and non-plastic waste, (2) the plastic composition and (3) the variation of plastic transport within the water column. Each trawl layer consisted of a metal frame (0.67 m wide, 0.5 m height) and a two-meter long net with a mesh size of 1.5 cm. The single layer trawl sampled from 0 to 0.35 m below the surface, the double-layered trawl from 0 to 0.35 m and 0.5 to 1.0 m below the surface. As the layer between 0.35 m and 0.5 m was not sampled, we assume that the samples of the two-layered trawl are representative for the layers between 0 to 0.425 m and 0.425 to 1.0 m depth. Organics and plastics was separated and subdivided (based on van Emmerik *et al* 2018) in the field into polyethylene terephthalate (PET), polystyrene (PS), expanded polystyrene (PS-E), soft polyolefins (PO_{soft}; low density polypropylene (PP) and polyethylene (PE)), hard polyolefins (PO_{hard}; high PP and PE), multilayer plastics (multilayer flexible packaging materials, mostly based on PE and PP) and rest plastics. Other material was classified as rest material. Sampling and visual counting measurements were done simultaneously. The duration of each sampling session depended on the flow velocity and plastic concentration, to not exceed the trawl loading capacity, and generally lasted between 1 and 10 min. At BKB-Grogol, the daily total sampled plastic mass and counted floating plastic items were used to establish an empirical relation to estimate plastic mass in the upper layer from visual counting of floating plastic.

2.3. Hydrodynamic model

To estimate the variation within a typical year of the discharge at monitoring locations and other locations of interest, we used a rainfall-runoff model with a hydrodynamic model (Budiyono *et al* 2016). The model is width and depth averaged (1D) and covers the main rivers (Ciliwung, Nagke and Pesanggrahan) and primary drainage channels (Cengkareng drain, Western Flood Channel (or Banjir Kanal Barat, BKB) and Eastern Flood Channel (Banjir Kanal Timur, BKT) and several secondary drainage channels. Rainfall was constructed by long-term averaged daily rainfall for an average year, ranging from 1500 mm in Jakarta to 4000 mm in upper Ciliwung catchments. In the Jakarta Bay, an astronomical tide was imposed. To estimate the total emission of Jakarta, we selected five locations with the largest river discharge into the ocean, i.e. BKB-Angke, Cengkareng Kapuk, BKT, Cakung and Sunter (see figure 1). As the discharge of the Sunter, the fifth largest river, is already 30 times lower than the discharge in the Ciliwung at BKB-Angke, the largest river, it is assumed that other drains and canals only emit a marginal amount of plastic.

2.4. Estimation plastic emission

We estimated plastic transport and emission for the two-week measurement period and for the whole year. First, we combined all observations to estimate plastic emission during the two-week measurement period. Visual counting measurements taken during trawl sampling were averaged to arrive at a daily mean floating number of plastic items per hour. Using mass

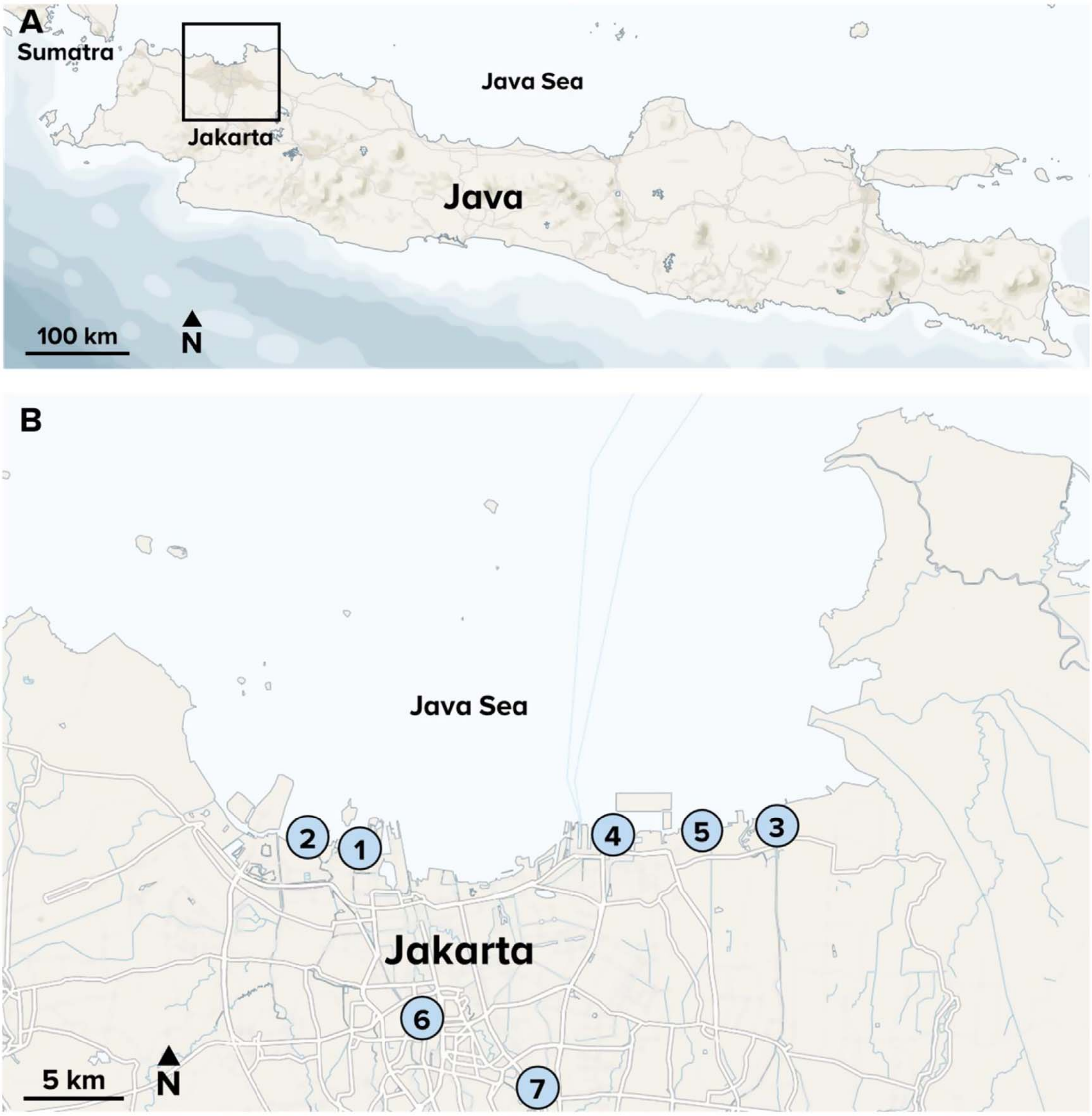

Figure 1. (A) Java, Jakarta and the Java Sea. (B) Overview of monitoring locations and hydrodynamic data locations in Jakarta, Indonesia. (1) BKB-Angke (Ciliwung), (2) Cengkareng Kapuk (Pesanggrahan), (3) BKT (various), (4) Sunter mouth (Sunter), (5) Cakung mouth (Cakung), (6) BKB-Grogol (Ciliwung), and (7) Haryono (Ciliwung).

statistics obtained from the trawl, plastic mass flux in the upper 35 cm of the water column was calculated. The plastic concentration measurements taken with the two-layer trawl yielded a vertical plastic mass profile within the first 1 m of the water column. This profile was used to determine a factor to multiply with in order to represent the mass in the top 1 m of the water column from the estimation of the mass in the upper 35 cm. The plastic mass in below 1 m depth was taken into account by assuming that 30% of the plastic mass occurs below 1 m depth, which was based on findings reported in Hohenblum *et al* (2015).

Second, we extrapolated the May observations to annual emission using monthly mean discharge as a scaling factor. Mean monthly discharge is provided through the hydraulic model (see section 2.3). The annual plastic emission from the unmeasured rivers is estimated by using the same distribution statistics (discharge ratio, see table 1) as the modeled discharge. Note that May is generally at the end of the wet season, and rainfall and discharge may be higher in other months, which may result in higher macroplastic transport for similar plastic concentrations than in May.

Recall that for our estimation, we only consider macroplastic debris larger than 1 cm which is either floating or suspended. Bed transport of plastic and plastic items smaller than 1 cm are not considered in this study.

3. Results

3.1. Floating plastic flux

The plastic flux varies considerably over the river width, with at each monitoring location a clear peak in the middle of the river (see figures 2(A)–(E)). The plastic distribution is related to flow velocity, and as the rivers in Jakarta are mostly channelized and straight, a peak in the center was expected. Daily average plastic transport

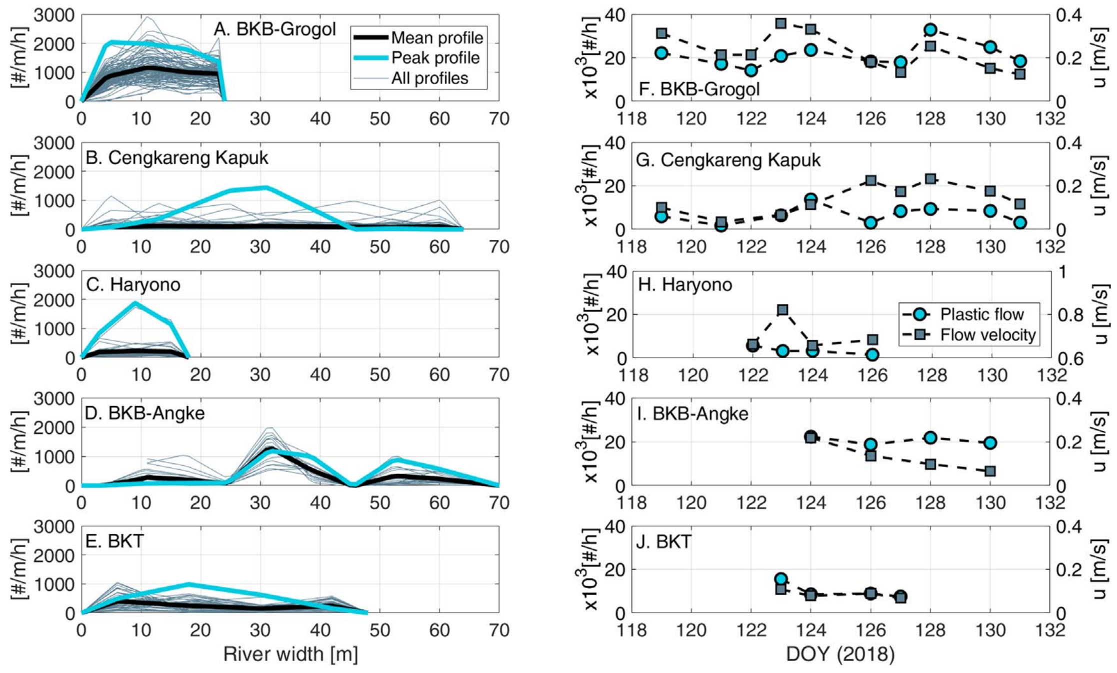

Figure 2. Floating plastic flux across the river/canal (A)–(E) in plastic items per meter width per hour, and daily averaged hourly plastic transport (F)–(J) in plastic items per hour and measured daily mean flow velocity for day of year (DOY) 118–131.

Table 1. Overview of measured and modeled river sections.

Location	River	Measured and/or modeled	Outlet to ocean (yes/no)	Discharge ratio
1. BKB-Angke	Ciliwung	Measured and modeled	Y	31.80%
2. Cengkareng Kapuk	Pesanggrahan	Measured and modeled	Y	16.40%
3. BKT	Various	Measured and modeled	Y	7.30%
4. Cakung	Cakung	Modeled only	Y	1.90%
5. Sunter Mouth	Sunter	Modeled only	Y	1.00%
6. BKB-Grogol	Ciliwung	Measured and modeled	N	N/A
7. Haryono	Ciliwung	Measured and modeled	N	N/A

showed some variation between measurement days. At BKB-Grogol (figure 2(F)), the plastic flux seems to follow the flow velocity, although the scaling factor between them changes over time. At Cengkareng Kapuk (figure 2(G)), the plastic flux follows the flow velocity in the first week, but shows a different pattern in the second. The concentration of macroplastics is higher in the second week. These results suggest that plastic transport is related to flow velocity, but also strongly depends on the temporal variation of input of land-waste plastic waste in river systems. On average, the mean hourly plastic flux ranged between 3×10^3 items h^{-1} (Haryono, figure 2(H)) and 20×10^3 items h^{-1} (BKB-Angke, figure 2(I); BKB-Grogol, figure 2(F)).

3.2. Plastic statistics

The plastic mass content of the sampled debris was found to be between 37% and 54% (see figure 3), which is considerably higher than found in, for example, the Saigon River (8%, van Emmerik *et al* 2018). At BKB-Grogol, it was found that the plastic mass content of the sampled debris was higher between 50 and 100 cm below the surface (52%) than at 0–35 cm (37%). Most of the plastic was identified as either PO_{soft} (38% mass) or multilayer (35% mass); see figure 3. The composition varied considerably between locations, with multilayer being the most abundant class at Haryono (68% mass) and BKB-Angke (49% mass), and PO_{soft} at Cengkareng Kapuk (57% mass) and BKB-Grogol (40% mass). The low share of PET can be explained by the informal recycling industry in Jakarta, which has increased the monetary value of PET items, and leads to active removal of PET items from rivers. Compared to sampled plastic in the Saigon River, Vietnam (van Emmerik *et al* 2018) some interesting differences can be observed. In Saigon, PS-E was the most observed plastic polymer. These results suggest that the plastic found in Jakarta might relate more directly to household waste than in, for example, Vietnam.

Total daily counted plastic items at the surface were empirically related to the total daily sampled plastic mass through simultaneous measurements at

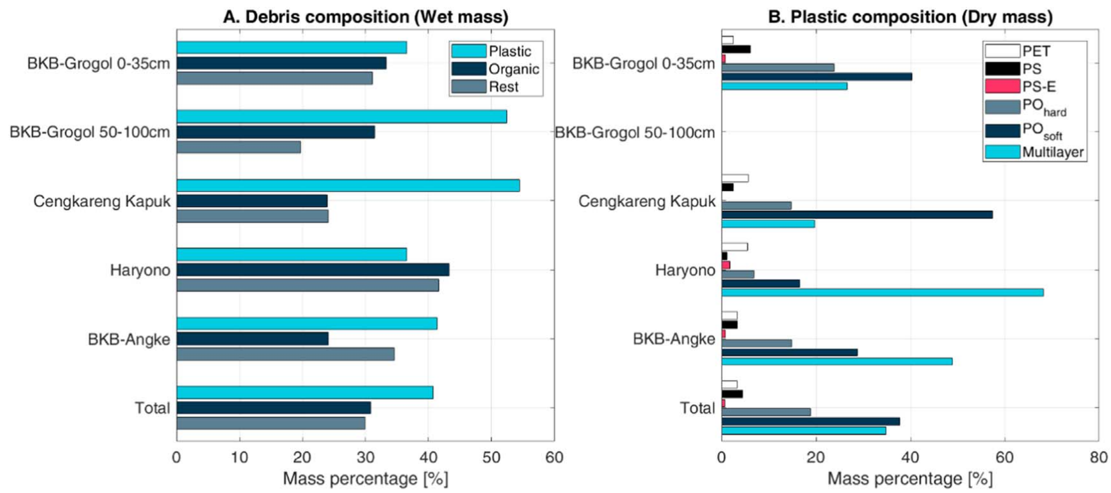

Figure 3. (A) Debris composition of the sampled mass and (B) plastic composition, at all five sampling locations.

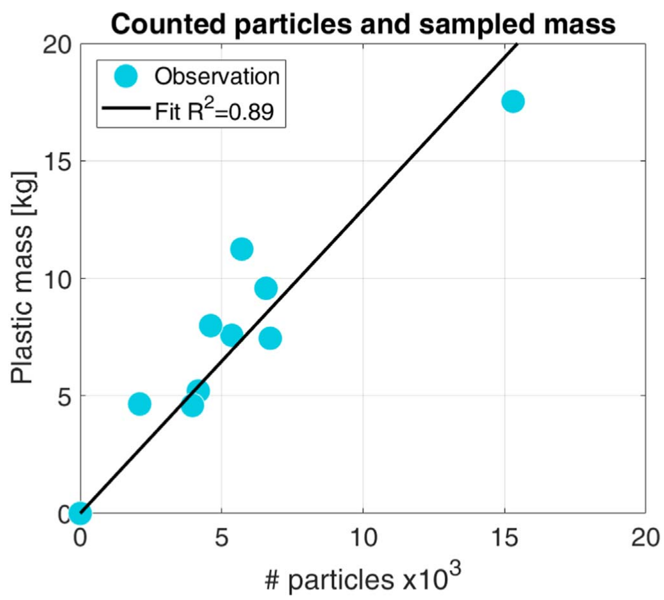

Figure 4. Relation between sampled plastic mass in the upper layer (0–35 cm below the surface) and counted plastic items at the surface at BKB-Grogol.

BKB-Grogol. Figure 4 presents the relation between the surface observations and the sampled mass in the upper layer (0–35 cm), which can be described well with a linear fit. From this relation, we derived a value for the mean mass in the upper layer per counted macroplastic item at the surface of 1.3 g per item. With this value, we estimated the mass in the upper layer from visual observations. We emphasize that this value may be variable in time and space, and for example be a function of plastic composition. As in this study, we only obtained such data for BKB-Grogol, we use this value in the assessments of each location.

Previous work on the Thames found a considerable amount of plastic flowing at deeper layers (Morrit *et al* 2014). In Jakarta, plastic was sampled at two depths at BKB-Grogol. Figure 5 presents the vertical plastic concentration profile, showing a clear decrease in plastic concentration at the lower layer (0.425–1.0 m). In the upper layer (0–0.425 m) the measured concentration was on average five times as high as in the lower layer. The plastic concentration was also found to vary considerably in time. Though the concentration in the top layer was always higher than at the lower layer.

3.3. Monthly discharge

Discharge in the Jakarta area shows a clear seasonal pattern, influenced by the rainy and dry seasons. Figure 6 demonstrates the variation in monthly averaged discharge as predicted by the hydrodynamic model for each of the five river outlets considered in this study. The sampling period was in May, which is

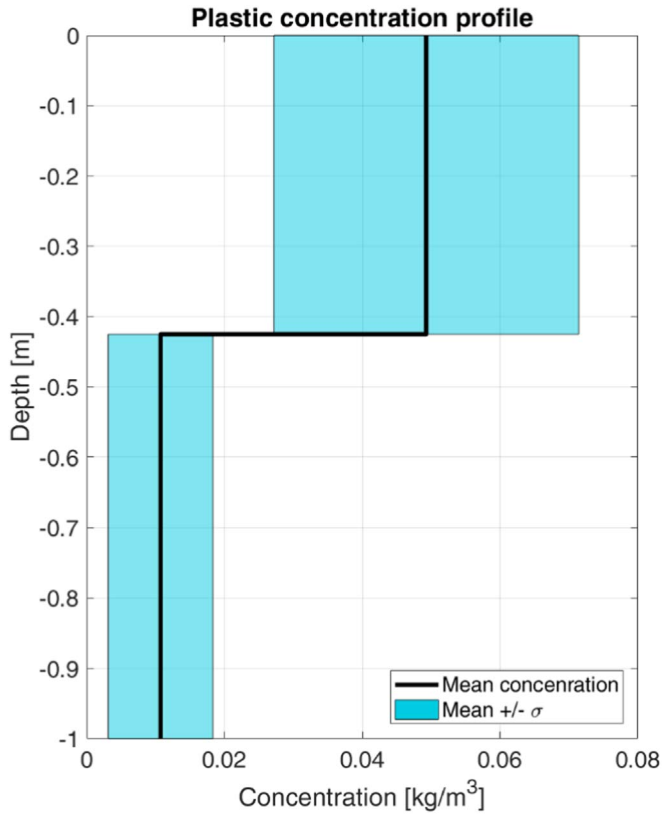

Figure 5. Daily mean vertical concentration profile at BKB-Grogol, mean and standard variation from 10 trawl sampling days.

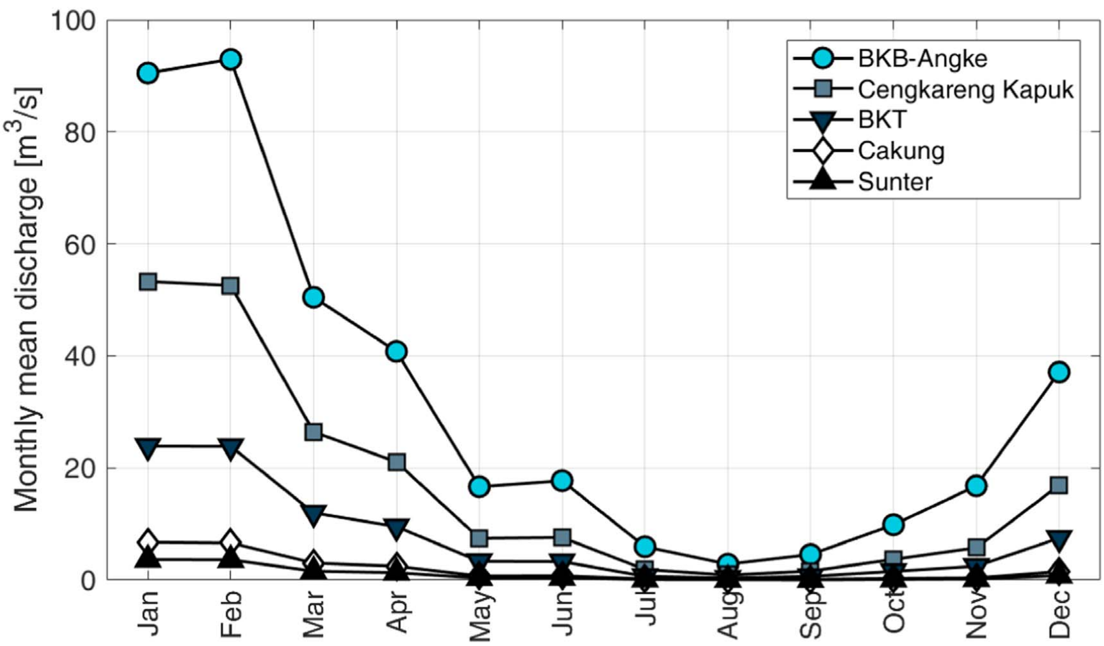

Figure 6. Monthly variation in discharge at the five outlets considered in this study.

at the end of the wetter season. The maximum discharge is expected in January or February, and the maximum is about five times higher than the discharge in May. Figure 6 also clearly demonstrates that the BKB-Angke contributes most to the total discharge, followed by the Cengkareng Kapuk. The Cakung and Sunter outlets only supply a marginal amount of discharge into the ocean.

Table 2. Overview of the measured mean and estimated yearly plastic transport for all sampled and modeled locations.

Location	River	Mean transport (May, 2018) (tonnes d^{-1})	Emission into the ocean? (Yes/No)	Yearly transport ($\times 10^3$ t yr^{-1})
BKB-Angke	Ciliwung	1.5	Y	1.0
Cengkareng Kapuk	Pesanggrahan	0.5	Y	0.4
BKT	Various	0.7	Y	0.6
Cakung Drain	Cakung	—	Y	0.1
Sunter Mouth	Sunter	—	Y	0.0
BKB-Grogol	Ciliwung	1.5	N	1.0
Haryono	Ciliwung	0.2	N	0.2
Total emission				**2.1**

3.4. Annual plastic mass transport

Using the monthly discharge derived with the hydrodynamic model and assuming that the plastic concentration is the same as during the two-week monitoring period, the annual plastic transport was estimated. On average, the highest plastic mass transport was estimated at BKB-Angke and BKB-Grogol (both 1.5 t d^{-1}, see table 2). Plastic mass flux at BKB-Angke and Cengkareng Kapuk (outlets into the ocean) is 2.5–7.5 times higher than at the upstream location (Haryono) of the Ciliwung, before it enters the more densely populated areas of Jakarta. This suggests that the majority of the plastic waste emitted into the ocean originates from the city of Jakarta. The total annual plastic emission into the ocean from the Jakarta rivers and canals is estimated to be 2.1×10^3 t yr^{-1}, with the clear majority coming from the Ciliwung (1.0×10^3 t yr^{-1}), BKT (0.6×10^3 t yr^{-1}) and the Pesanggrahan (0.4×10^3 t yr^{-1}); see table 2.

4. Discussion

Around 2.9×10^5 tonnes yr^{-1} of plastic waste is produced in Jakarta, of which 25% is disposed unsoundly (Waste Atlas 2019). The estimated 2.1×10^3 tonnes yr^{-1} plastic emission into the ocean through rivers and canals therefore equals 3% of the total annual mismanaged plastic waste in Jakarta. This emphasizes the need for the following future assessments of estimating macroplastic transport to optimize collecting these plastics before they are transported to the sea. Note that the total plastic emission may also include (plastic) waste from more upstream areas towards the ocean. First, accumulation of mismanaged plastic waste on land and within the river should be quantified. A better understanding of the factors influencing plastic transport over land and within river systems will contribute to the improvement of riverine plastic transport modeling approaches.

This assessment is mainly based on daily and monthly averaged values for flow velocity and rainfall. However, extreme (and rapid) flooding events may (re)mobilize additional plastic waste, increasing riverine plastic emission into the ocean. In our estimate, we assume that the plastic concentration remains at the same level as observed during the two-week monitoring period in May throughout the year. We do hypothesize that flood events might mobilize additional plastic debris such that the plastic concentration may be higher than during the two-week monitoring period. At the other hand, we do not consider that the plastic concentration may be limited by supply during high discharges, which can in turn reduce the plastic concentration. Peak debris flow generally happens during flood events (Minami *et al* 2015), and we expect that in urban areas this is the same for plastic debris flow. Floods are a continuous threat for the city of Jakarta, mainly during the rainy season between December and March. Unfortunately, accurate information on floods, especially during the first hours, are scarce (Eilander *et al* 2016). Future work should consider studying the effect of flood events on plastic transport, as that will contribute to a better understanding of all driving forces of riverine plastic transport. The macroplastic transport of 2.1×10^3 t yr^{-1} is a central estimate, showing that transport from the Jakarta rivers and canals contributes at least to 1% of the emission estimated by Lebreton *et al* (2017) for the whole of Indonesia. This is much higher than the percentage of the drainage basin area in comparison with the Indonesia land surface (0.05%), showing that the plastic transport from the rivers and canals running through Jakarta is at least about 20 times higher than the Indonesian average.

To arrive at an annual estimation of plastic emission we used several empirical relations. For this study, these are based on observations at a single location (BKB-Grogol), and consecutively applied to the other locations. A source of uncertainty may be introduced here, as such empirical relations may depend on local plastic composition and river characteristics. Therefore, we recommend establishing empirical relations at each study location in future assessments. Riverine plastic research is an emerging field in science, and such empirical relations may contribute to a more generalist understanding of transport mechanisms.

Understanding the vertical distribution also remains a crucial uncertainty in the assessment of riverine plastic flux. Previous work has suggested that plastic flux at deeper layers may be a significant share of total plastic flux. In the Thames, plastic was sampled just above the river bed (Morritt *et al* 2014). Considerable amounts of plastic were found, although no sampling of plastics at the surface was done for comparison. In the Danube, sampling at three layers showed that 66%–79% of the total plastic was found below 1.5 m depth (Hohenblum *et al* 2015). We expect that the vertical distribution of plastic transport depends strongly on the composition of plastic debris and its degree of degradation or biofouling. In turn, we expect that the assumed percentage of 30% of transport below 1 m depth may not be representative for the rivers studied in this paper, or other rivers around the world. Sampling at deeper layers requires additional infrastructure, such as cranes or boats. As the current understanding and data availability is limited, we do recommend investing in assessments of the complete vertical profile of riverine plastic transport.

Accurate estimates of plastic emission from the Jakarta waterways also provide input for assessments of the fate of plastics entering the Jakarta Bay. A recent plastic particle tracking assessment using a 2D hydrodynamic flow model for the Jakarta Bay demonstrated that a considerable share of the plastics emitted from Jakarta remained in near-shore areas (Karlsson and Nordén (2018)). This may pose additional risks to shipping activities (McIlgorm *et al* 2011). Furthermore, these plastics may wash ashore on the Java coast, resulting in increased amounts of beach litter, damaging ecosystems and tourist activities (Schwarz *et al* 2019). Finally, some portion of the emitted plastics will travel to the open sea. Given that most emitted plastics were found to be bags and foils, these most likely end up on the ocean floor in the Java Sea or beyond (Schwarz *et al* 2019).

This paper presents a first estimation of riverine plastic emission into the ocean from a dense coastal urban area. Recent global estimations of riverine plastic emission are based on catchment scale lumped models (e.g. Lebreton *et al* 2017, Schmidt *et al* 2017). Such approaches use topography derived river flow paths, and do not consider any anthropogenic influences (canalization, urban drains, hydraulic structures). More detailed assessments, as presented in this paper, give additional insights in the origin and fate of riverine plastic pollution originating from Jakarta. Especially for the evaluation of potential mitigation and collection strategies, such local studies are of crucial importance.

5. Concluding remarks

By combining results from a two-week monitoring campaign and a hydrodynamic model, the total plastic emission of the rivers and canals running through Jakarta is estimated to be 2.1×10^3 t yr^{-1}. Although this may also include plastics from Jakarta's upstream areas, the annual emission equals 3% of the city's total annual unsoundly disposed plastic waste. The majority is discharged through drains of the Pesanggrahan and Ciliwung rivers.

Empirical relations between plastic transport and hydrology were used to improve the estimations of total plastic transport in Jakarta. Future assessments can make use of similar simple short period observations, the same relations and hydrodynamic model results to extrapolate of time, to estimate the macroplastic transport at first order.

Sampled plastic mass consisted mostly of multilayer and PO_{soft} (bags, films and foils), reflecting the waste management practices and consumption patterns of the surrounding population. The composition may vary considerably between rivers.

Riverine plastic is an emerging scientific field, and field assessments are still limited. With this paper, we aim to provide new insights in the occurrence and spatiotemporal variation of riverine plastic transport in dense, coastal cities. Future assessments remain crucial to increase riverine plastic data availability, which will contribute to improving our understanding of riverine plastic transport and evaluate potential mitigation measures.

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Data availability statement

The plastic sampling data is available as supplementary material (available online at stacks.iop.org/ERL/14/084033/mmedia). The hydrodynamic model data may be obtained from Frans Buschman.

Author contributions

T v E, M L and K v O designed the study. M L and K v O conducted the fieldwork. M L and T v E performed the initial data analysis. F B and G P provided hydrodynamic model results. T v E wrote the initial manuscript. T v E and F B wrote the final manuscript. All authors contributed to interpretation of results and revising the manuscript.

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