# Discontinuity in fluvial plastic transport increased by floating vegetation

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**Abstract**

Understanding plastic mobility in rivers is crucial in estimating plastic emissions into the oceans. Most studies have so far considered fluvial plastic transport as a uniform process, with stream discharge and plastic concentrations as the main variables necessary to quantify plastic transport. Decelerating (e.g.: trapping effects) and accelerating effects (e.g.: increased water flows) on plastic transport are poorly understood, despite growing evidence that such mechanisms affect riverine plastic mobility. In this observation-based study, we explored the roles of an invasive floating plant species (i.e. water hyacinths) as a major disruptor of plastic transport. The different functions of aquatic vegetation in trapping and transporting plastics play a key part in our evolving understanding of how plastic moves in rivers. We collected a one-year dataset on plastic transport, densities and hyacinth abundance in the Saigon river, Vietnam, using both a visual counting method and UAV imagery analysis. We found that hyacinths trap the majority of floating plastic observed (~60%), and plastic densities within patches are ten times higher than otherwise found at the river surface. At a monthly and seasonal scale, high hyacinth coverage coincides with peaks in both plastic transport and densities over the dry season (Dec-May) in the Saigon river. We also investigated the large-scale mechanisms governing plant-plastic-water interactions through a conceptual model based on our observations and available literature. Distinguishing total and net plastic transport is crucial to consider fluctuations in freshwater discharge, tidal dynamics and trapping effects caused by the interactions with aquatic vegetation and/or other sinks.

# Discontinuity in fluvial plastic transport increased by floating vegetation

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**Key Points:**

- Water hyacinths are major plastic sinks, with plastic densities up to ten times higher than at the river surface.
- Plastic transport, plastic densities and hyacinth abundance are closely linked, with timing and location of accumulation coinciding.
- Hyacinth coverage and plastic densities are affected by fluctuations in river discharge which in turn impact plastic transport seasonality.

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In this observation-based study, we explored the roles of an invasive floating plant species (i.e. water hyacinths) as a major disruptor of plastic transport. The different functions of aquatic vegetation in trapping and transporting plastics play a key part in our evolving understanding of how plastic moves in rivers. We collected a one-year dataset on plastic transport, densities and hyacinth abundance in the Saigon river, Vietnam, using both a visual counting method and UAV imagery analysis.

We found that hyacinths trap the majority of floating plastic observed (~60%), and plastic densities within patches are ten times higher than otherwise found at the river surface. At a monthly and seasonal scale, high hyacinth coverage coincides with peaks in both plastic transport and densities over the dry season (Dec-May) in the Saigon river.

We also investigated the large-scale mechanisms governing plant-plastic-water interactions through a conceptual model based on our observations and available literature. Distinguishing total and net plastic transport is crucial to consider fluctuations in freshwater discharge, tidal dynamics and trapping effects caused by the interactions with aquatic vegetation and/or other sinks.


## 1 Introduction

Plastic pollution poses a series of threats to global ecosystems, including aquatic systems such as rivers. High levels of plastic pollution in rivers can reduce availability of potable freshwater, cause damage to urban infrastructure, and potentially harm the local fauna (van Emmerik & Schwarz, 2020). Rivers are considered the main pathways for land-based plastic emissions into the oceans (Meijer et al., 2021). In addition, rivers can also retain plastics for decades, if not longer (Tramoy et al., 2020). Understanding plastic mobility in rivers is therefore crucial for risk assessments for riverine ecosystems under variable plastic concentrations, and for accurate estimations of emissions into the oceans.

Rivers have long been considered as simple conduits for plastic transport to the sea. Many studies portrayed the plastic journey in rivers to be a continuous trajectory of particles through a uniform medium that offers little to no resistance to its final export into coastal waters. As a result, plastic transport in rivers is often quantified as a direct function of plastic concentrations in the water and river discharge (Schmidt et al., 2017; van Emmerik et al., 2018; Haberstroh et al., 2021). However, recent scientific advances have shed light on the discontinuous dynamics at play in fluvial plastic transport; at both temporal and spatial scales. Temporally, plastic transport rates have been observed to follow seasonal patterns and transport in various rivers (van Emmerik et al., 2019; van Emmerik, de Lange, et al., 2022), at times linked to seasonal variation in freshwater discharge. In addition, extreme discharge events such as floods lead to disproportionally increased plastic transport rates (Hurley et al., 2018; Roebroek et al., 2021; van Emmerik, Frings, et al., 2022). Spatially, changes in river shape such as meander bends and the presence or absence of physical barriers can lead to varying trapping rates, which affects plastic propagation in the water (Newbound, 2021). Physical traps or barriers include infrastructure such as damns, groynes, bridges and weirs, as well as bank and aquatic vegetation. These impediments can physically retain plastic items temporarily or even permanently (Cesarini & Scalici, 2022; Schreyers, van Emmerik, Luan Nguyen, Castrop, et al., 2021; Skalska et al., 2020). In addition, varying plastic concentrations caused by human behaviours along the river (plastic leakage and removal) contributes to spatially varying plastic transport rates. These discontinuities likely lead to accelerating or decelerating effects of plastic distribution and propagation in the water, similarly to what is observed for other floating debris such as wood (Wohl, 2017; Wohl & Scott, 2017). As such, these discontinuities challenge the common assumption of a uniform and unidirectional effect of river discharge on plastic mobility.

Aquatic vegetation can disrupt plastic mobility in rivers physically, spatially and temporally, and could therefore generate discontinuous effects in fluvial plastic transport. Vegetation can trap plastic items, therefore leading to deposition and transport mechanisms that are affected by water-plant-plastic interactions (*physical discontinuity*). Vegetation coverage varies due to the seasonal cycle, which, in turn, leads to higher or lower plastic retention rates depending on the period of the year considered (*temporal discontinuity*). Small scale variations in vegetation abundance along and/or across a given river might also alter both plastic transport and deposition rates (*spatial discontinuity*). Here, we explore the discontinuous nature of fluvial plastic transport by focusing on the role of an aquatic vegetation species (e.g.: water hyacinths, *Eichhornia crassipes*) in trapping plastics in the Saigon River. Hyacinths function as a major aggregator of floating macroplastics in tropical rivers and can, therefore, act as a dominant control factor of fluvial plastic transport (Schreyers et al., 2021a; Schreyers et al., 2021b). These invasive aquatic species are now present in most tropical lakes and rivers worldwide (CABI, 2020; Thamaga & Dube, 2019), and their coverage of water surfaces can double in within one to two weeks due to their rapid growth rate (Ouma et al., 2005). As a surface plant species, hyacinth float in patches of varying sizes and densities. Their drift patterns are passive, and spatial distributions are influenced by factors such as currents and wind. In low flow conditions, hyacinths can rapidly blanket a large portion of the waterway. Kleinschroth et al. (Kleinschroth et al., 2021) found that for small reservoirs, peaks in hyacinth coverage often exceeded 80% of the total reservoir area. Conversely, in more active systems like rivers, hyacinth coverage tends to be lower due to the transport of the plants with water flow, but can still reach up to 25% of the river surface (Janssens et al., 2022). Previous field-based studies have successfully shown that hyacinths play a crucial role in fluvial plastic transport, however, these observations were conducted over a short measurement period (6 weeks) and at only one location. This study provides a much-needed more comprehensive understanding of how hyacinth abundance alters fluvial plastic transport over both time and space.

For the present study, we monitored hyacinth coverage, plastic transport and plastic densities in the Saigon river, Vietnam, over one year. The Saigon river has one of the highest plastic transport rates in the world and is severely impacted by hyacinths invasion (van Calcar & van Emmerik, 2019; Janssens et al., 2022). We hypothesize that hyacinths function as a major temporary sink for riverine plastics and that therefore temporal peaks and spatial accumulation zones in hyacinth coverage generally coincide with high plastic loads. We first established the overall role of hyacinths as temporary traps for plastic items (section 3.1). We then investigated the evolution of the measured metrics (e.g.: hyacinth coverage, plastic transport and densities) at various temporal scales (seasonally, monthly and daily) to characterize synchronous or asynchronous trends in transport and accumulation (section 3.2). In addition, we analyzed how these variables are spatially distributed in the river system, between upstream and downstream locations along the river and across the river channel (section 3.3). The first part of this study focuses on quantifying hyacinth's role as a temporary and mobile sink of floating plastic based on our field observations (section 3. Results and Discussion). In the second part, we further expand on the interactions between plastic-plant-water at a system scale (section 4. Synthesis and Conceptual model). We first summarize our main findings which identified different modes of plastic transport in the river in relation to hyacinth coverage (section 4.1). We present a conceptual model based on these observational findings and our broader understanding of the fluvial system investigated, to explain spatio-temporal variations in plastic transport (section 4.2). We thus synthesize the discontinuous effects induced by hyacinth abundance on plastic transport (section 4.3) and finally identify next steps in future research effort that seek to understand large-scale plastic transport and deposition processes in fluvial systems (section 4.4). The outcomes of this study are useful for scientists seeking to understand large-scale fluvial plastic transport and deposition mechanisms. In addition, river plastic monitoring and reduction strategies might seek to opportunistically use (temporary) sinks because of their role in aggregating large quantities in floating plastics.

## 2 Data and Methods

### 2.1 Study area

We measured plastic transport, hyacinth abundance and plastic densities between December 12, 2020 and January 15, 2022 at the Saigon river, Vietnam (Fig. 1 and Table 1). The Saigon river originates in Cambodia and flows into the Dau Tieng reservoir, approximately 120 km north from Ho Chi Minh City (Nguyen et al., 2020). The river crosses agricultural areas of paddy rice and rubber plantation before entering the city. South of the city, the Saigon river confluences with the Dong Nai river. There, the Dong-Nai-Saigon river system branches into several channels that meanders in the Can Gio mangrove forest before entering the East Sea (Dijksma et al., 2010). The Saigon river is subject to asymmetrical semi-diurnal tidal cycle. Because of the tidal influence, the net river discharge is considered relatively low and subject to seasonal variations between the dry and wet seasons (monthly averages vary between -80 and 320 $m^3/s$) (Camenen et al., 2021). In addition, the Saigon river is considered one of the most plastic polluted rivers worldwide, with transport rates within the order of $10^4$ items/hour (van Calcar & van Emmerik, 2019). Hyacinth invasions are also particularly severe in this river, with peak coverage reaching up to 14% of the river surface (Janssens et al., 2022).

This study focuses on floating macroplastic (>0.5 cm of size) density and transport, hereafter referred to as plastic. Plastic transport was measured at two locations in Ho Chi Minh City (Fig. 1). The first site (L1) is located north of the city (10.89025, 106.69209) and the second (L2) in its southern part (latitude: 10.785984; longitude: 106.718332). The two monitored sites approximately 30 km apart. At Ho Chi Minh City, the Saigon river progresses from north to south, therefore enabling to compare upstream and downstream plastic transport values within the urban area. Plastic transport was measured using the visual counting method for floating bridges from bridges (section 2.2), and hyacinth abundance and plastic density were measured using Unmanned Aerial Vehicle (UAV) imagery analysis (section 2.3 and 2.4). Flying at the downstream site was deemed unfeasible for long-term monitoring, due to the proximity of a military site. For this reason, UAV surveys were only conducted at L1. UAV images were taken across the river channel, with a frequency of one to four flights per measurement day. Each flight consisted of two overpasses across the Saigon river, with a range of 41 to 65 images taken per flight. UAV surveys were carried at a constant elevation of approximately 10 m above the water level. More information on the UAV surveys is available in Supporting Information (Extended Methods). Table 2 summarizes the measurement frequencies per month at each location. Data gaps are noticeable for certain months: no data could be collected for any of the variables investigated in August and September 2021. Due to the COVID-19 pandemic, a strict confinement was mandated in Ho Chi Minh City, thus not allowing observers to leave their houses. A larger data gap is noticeable for hyacinth abundance and plastic densities, with no measurements conducted in April, July and October 2021. The gap during the month of April was due to the unavailability of the observer conducting the UAV flights. The missing data from July and October 2021 was also caused by COVID-19 restrictions. In those months, the government did not allow inhabitants to cross the border between two different provinces, thus not enabling access to the UAV flying site at L1 (a few hundred meters upstream of where the visual counting measurements were conducted).

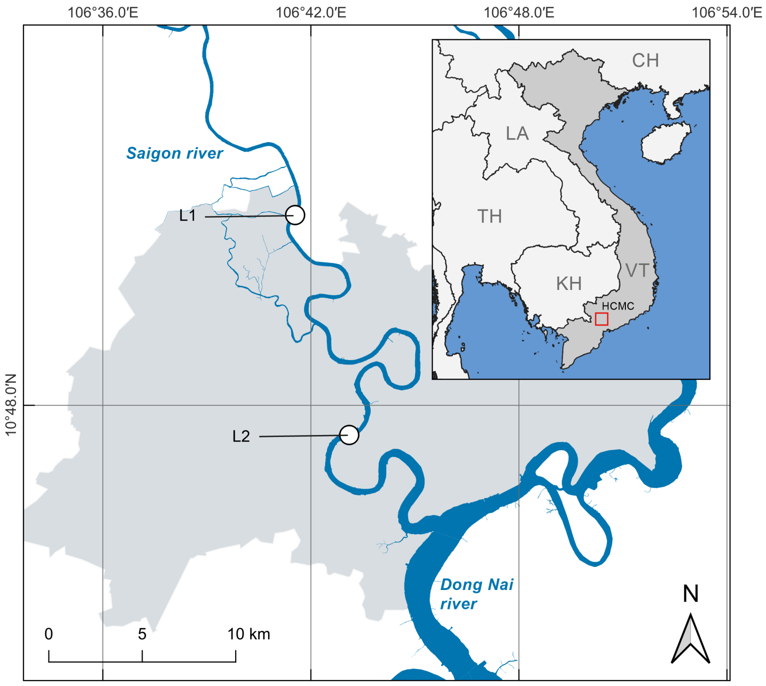


Figure 1: Localization map of monitored sites in Ho Chi Minh City (HCMC), Vietnam and measurement frequency at each location.

Table 1: Measurement frequency at each location. Total refers to the total number of UAV images analyzed in the case of hyacinth abundance and plastic densities. For plastic transport, it refers to the total number of observations, with one observation corresponding to a measurement per observation segment.

| | **Measurement locations** | | | |
|---|---|---|---|---|
| | L1 | | L2 | |
| | *Total* | *Daily* | *Total* | *Daily* |
| Plastic transport | 900 | 49 | 1,272 | 51 |
| Hyacinth abundance | 3,544 | 29 | N/A | N/A |
| Plastic densities | 2,360 | 29 | N/A | N/A |

Table 2: UAV images and plastic transport measurement frequency per month. The values here refer to the total number of UAV images for hyacinth abundance and plastic density. For plastic transport, the reported values correspond to the total number of observations. Blank cells indicate that no observations were conducted for that period.

| | Number of measurements by month | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dec 20 | Jan 21 | Feb 21 | Mar 21 | Apr 21 | May 21 | Jun 21 | Jul 21 | Aug 21 | Sep 21 | Oct 21 | Nov 21 | Dec 21 | Jan 22 |
| Plastic transport (L1) | 54 | 108 | 72 | 126 | 126 | 90 | 54 | 36 | | | 18 | 90 | 90 | 36 |
| Plastic transport (L2) | 84 | 144 | 83 | 168 | 168 | 120 | 72 | 46 | | | 89 | 110 | 110 | 44 |
| Hyacinth abundance (L1) | 142 | 536 | 141 | 935 | | 407 | 186 | | | | | 550 | 363 | 284 |
| Plastic densities (L1) | 105 | 388 | 108 | 391 | | 376 | 95 | | | | | 435 | 192 | 274 |

### 2.2 Floating plastic transport

Plastic transport were estimated using the visual counting method, developed by (González-Fernández & Hanke, 2017) and now widely used in observational studies on macroplastic transport (González-Fernández et al., 2021; van Calcar & van Emmerik, 2019). All floating macroplastic and macrolitter items (>0.5 cm) floating at the river surface were counted during a determined time frame at each observation segment. Several observation segments were determined per measurement location, to account for the spatial variability in plastic transport across the river width (van Emmerik et al., 2018). The number of segments depends on the river width of the measurement location. Nine observation segments were selected at L1 (upstream site, river width of 200 m) and twelve at L2 (downstream site, river width of 300 m), enabling to cover respectively 68% and 60%. At each observation segment, two types of observation were conducted: counting of *entrapped* macroplastic and macrolitter, i.e.: items entrapped in hyacinth patches and counting of *free-floating* macroplastic and macrolitter, i.e.: items freely floating at the water surface.

The mean plastic transport observation $F$ [items/hour] for observation point $i$ was calculated using the following equation:

$$F_i = \frac{N_{t,i}}{t_{t,i}} + \frac{N_{f,i}}{t_{f,i}} \tag{1}$$

Here, $N_t$ is the plastic count of items [items] *trapped* in hyacinths and $N_f$ plastic count of *free-floating* items [items] for observation point $i$ during observation $t_t$ and $t_f$ [min], respectively. This distinction between trapped items and free-floating items enables to calculate the ratio of total trapped items over the total count of items, which is reported as a percentage [%]. The total floating plastic transport $F_{total}$ [items/hour] was calculated using the following equation, derived from van Emmerik, de Lange, et al. (2022):

$$F_{total} = \sum_{i=1}^{n} \frac{F_i}{w_i} \cdot W \tag{2}$$

Here, $w_i$ is the observation segment width [m], $W$ the total river width [m]. The observation track width $w_i$ [m] was estimated at 15 m for both measurement locations. We extrapolated floating plastic transport at an annual scale, considering both the mean and median $F_{total}$ for all measurements done over the monitored period, thus calculating both the mean and median annual item transport [million items/year]. We also expressed floating plastic transport in terms of mass transport [tons/year], using the following equation (Vriend et al., 2020):

$$M = F_{total} \cdot \overline{m} \tag{3}$$

Here, $\overline{m}$ expresses either the mean or the median mass per plastic item. We used both mean and median mass because other studies found that plastic transport estimates vary greatly depending on mass statistics (van Emmerik, de Lange, et al., 2022). We used the mass statistics from van Emmerik et al. (2019), who collected and weighted 3,022 items over 45 measurement days at the Saigon river. The mean mass was approximately 10 grams and the median mass 4.3 grams.

### 2.3 Hyacinth abundance

Hyacinth patches were detected using UAV imagery analysis. We used a color filtering approach which enables to separate floating vegetation content from other elements present at the river surface (e.g. water, banks, boats, wooden debris, floating items). This approach leverages the color characteristics of active vegetation in the visible range to distinguish it from other materials. A total of 3,562 UAV images was collected throughout the measurement period. To characterize hyacinth abundance, 3,544 images were ultimately processed. A few images (n = 18) were discarded because these were blurry, taken with a side-angle or due to the presence of boats which interfered with the hyacinth detection. Image processing was done using the Open CV 4.5.4.60 library in Python 3.9.7. In addition to the color filtering, we performed morphological operations over the images, involving noise reduction and dilation to close small gaps. These operations and related parameters are detailed in Supplementary Material (Extended Method). A minimum threshold area (>=0.1 $m^2$) was also defined to filter out individual leaves and branches. All these operation parameters were defined by trial and error through visual inspection, which was performed through a subset of the total UAV image dataset. Trial and error sought to maximize detection and minimize false positives as well as accurately detect the edges of the hyacinth patches. Physical sampling of the patches to estimate plastic densities was not deemed feasible for long-term monitoring, given that the patches typically move within minutes. More details on the processing steps performed and their validation can be found in the Supporting Information (Extended Method). Fig.2 provides an example of hyacinth detection for one UAV image.

We quantify hyacinth abundance in terms of coverage and count of patches. Hyacinth coverage [$km^2/km^2$] was calculated as the total area covered by hyacinth over the total river area considered. The count of patches [#] is expressed as the number of total patches found per measurement unit. For both variables, four measurement units/scales were retained: image, flight, day and month. We include statistics on the mean size of hyacinth patches [$m^2$] in section 2.3.

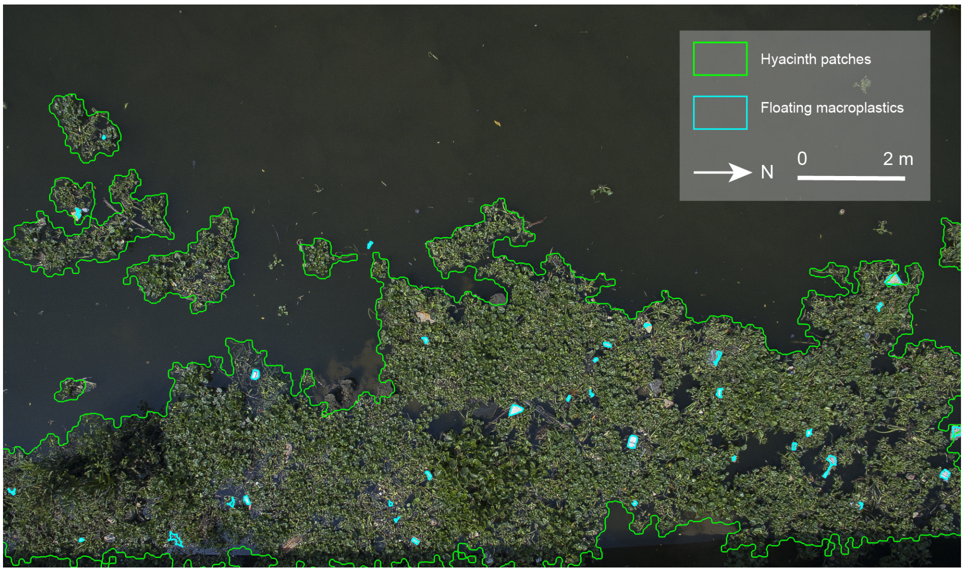


Figure 2: Example of processed UAV image [from 2 February 2021] with floating macroplastics and hyacinth patches identified.

### 2.4 Plastic densities

Plastic densities at the river surface and within hyacinth patches were also quantified using UAV imagery analysis. The approach chosen is similar to the one described for hyacinth detection in the previous section. The detection of floating plastic relied also on a color filtering operation, which filtered pixels of white and light grey color. This approach does not enable to detect all floating macroplastic and macrolitter items, which can be of varying colors, and opacity and transparency levels. However, our visual assessment on the entire dataset led to the conclusion that the majority ($\sim$ 70-90%) of macroplastic and macrolitter items were of this color range. This is consistent with previous studies that quantified macrolitter composition in the Saigon river and demonstrated the high proportion of items such as expanded polystyrene (food packaging, insulation foam), polystyrene (plastic cups and cutlery) and soft polyolefins (plastic bags and foils) (Schreyers, van Emmerik, Luan Nguyen, Castrop, et al., 2021; van Emmerik et al., 2019). Because of this limitation, our estimates of plastic densities should be considered conservative. In addition to the color filtering, morphological operations were also applied to the UAV imagery dataset, i.e. noise reduction with Gaussian filtering and closing of gaps. Overall, processing steps for plastic detection were less computer-intensive than for hyacinth patch detection, mainly due to the smaller size of the objects of interest and the broader homogeneity of items compared to hyacinth patches (edges were more easily distinguished for these anthropogenic items than for the rather loose patches). Additional details on the processing operations and their parameters can be found in the Supplementary Material (Extended Method). An example of plastic detection for one UAV image can be seen on Fig. 1.

Plastic detection could only be implemented after manually removing (by cropping) the area affected by sun glint from each image. Sun glint pixels have the same color characteristics as the detected plastics. Cropping was therefore necessary to avoid false positive detection. Given that many images had a very large glint area, many were completely discarded for plastic detection (n = 1,202). More information on these aspects can be found in the Supporting Information (Extended Methods).

We calculated two types of plastic densities: river surface plastic density, expressing the number of items over the total river area considered and hyacinth plastic density [items/km$^2$], expressing the number of items over the total hyacinth area considered. Plastic densities were expressed both as items densities [items/km$^2$] and mass densities [kg/km$^2$]. For mass densities, we used both the mean and median mass values per plastic item derived from van Emmerik et al. (2019), as described in section 2.2.

### 2.5 Additional data

To better understand plastic and hyacinth abundance in the Saigon river in relation to hydrological processes and their seasonality, we used available data on rainfall and freshwater discharge at the Saigon river. Rainfall and freshwater discharge are measured daily and the resulting datasets are openly and freely available on the website of the Ho Chi Minh City Irrigation Service Management company (http://www.dichvuthuyloi.com.vn/vn/tin-tuc/thong-tin-ve-tinh-hinh-dien-bien-khi-tuong-thuy-van-719/). We extracted all available daily data on rainfall and freshwater discharge at the Saigon river for the year 2021, corresponding to the measurement period for plastic transport, hyacinth abundance and plastic densities. We used the rainfall data measured at the station Mac Dinh Chi, located in the first district of Ho Chi Minh City (latitude: 10.784223242113756; longitude: 106.69904438238632), as this is the closest rainfall measurement station from our measurement sites. River discharge is not measured within Ho Chi Minh City. River discharge is measured in the Tây Ninh province, in the upstream area of the Saigon river and measurements correspond to the Dau Tieng reservoir inflow into the Saigon river. Monthly cumulative rainfall [mm] and mean freshwater discharge [m$^3$/s] were calculated based on the above-mentioned rainfall and discharge data and are presented in Fig. S2.

### 2.6 Statistical analysis

The variables presented in the previous sections were aggregated at various temporal scales to identify temporal trends. We aggregated values by seasons, with the dry season spanning from December to May and the wet season from June to November, as rainfall and water flow seasonality are key components of the hydrological regime of the Saigon river (Camenen et al., 2021). To test whether the mean ranks of hyacinth coverage, plastic densities and plastic transport are significantly different between dry and wet seasons we used the Kruskal-Wallis test, which does not assume a normal distribution of the data. For the daily and monthly aggregation levels we tested the Spearman correlations between pairs of variables. The spatial distribution of plastic densities, plastic transport and hyacinth coverage across the river was also investigated. The averaged cross-sectional spatial distribution was calculated based on daily means for the metrics considered. We tested the similarity in spatial distribution also using Spearman correlations. We characterized different regimes (see Results and Discussion, section 3.2) of plastic transport and hyacinth coverage. For this, we used the median values to distinguish between high and low categories of transport and coverage values.

# 3 Results and Discussion

## 3.1 Plastic density in hyacinths ten times higher than at river surface

On average, between 55% and 65% of floating macroplastic is being transported by hyacinth patches, depending on the location and the flow direction considered (L1, landward: 65%, seaward: 55%; L2, landward: 56%, seaward: 57%). We found that hyacinths cover an average of 6% of the river surface, therefore indicating that patches trap much more floating debris than could be hypothesized solely based on their relative coverage of the river surface. This is confirmed by the discrepancies observed between river surface and hyacinth plastic densities, with the latter being approximately one order of magnitude higher than the former (mean river surface plastic density: $2.5 \cdot 10^4$ items/km$^2$ and mean hyacinth plastic density: $2.1 \cdot 10^5$ items/km$^2$) (Table 3). These results confirm that hyacinths act as physical traps for floating plastics. Plastic transport in fluvial systems affected by hyacinth invasion are therefore not only influenced by the two-way interactions between water and particles, but are also likely affected by the movement of hyacinth at the water surface and changes in patch coverage. These include the growth and reduction of individual patches, as well as the aggregation and separation of patches among themselves.

Plastic item transport was estimated on average between 109 and 372 million items/year, for L1 and L2 respectively (Table 3), approximately two orders of magnitude higher than the top plastic polluted rivers in Europe (González-Fernández et al., 2021). Mean and median plastic mass transport estimates vary by a factor of approximately two (Table 3), depending on whether a mean or median mass per item was considered. This highlights the uncertainties associated with estimating plastic mass transport values. In addition, our estimates focus on the total plastic transport (i.e. the total volume of plastic being transported in the river, irrespective of the flow direction). Given that the Saigon river is strongly affected by tidal dynamics, a distinction between total and net plastic transport (i.e. the total volume of outgoing plastic) should be made in further studies and will be further discussed in section 4 (Synthesis and Outlook).

Mean item plastic densities at the river surface are 36 times higher ($2.5 \cdot 10^4$ items/km$^2$) than those found in the Great Pacific Garbage Patch (GPGP) ($6.9 \cdot 10^2$items/km$^2$) (Lebreton et al., 2018). The average plastic mass densities found at the river surface (102-250 kg/km$^2$ for mean and median mass densities, respectively) are 3 to 6 times higher those observed in the GPGP (mean mass density: 42 kg/km$^2$), a likely result of the heavier items found in the ocean compared to river plastic. The highest plastic density found in our observations ($4.7 \cdot 10^5$ items/km$^2$) is 190 times higher than the top density for the GPCP ($2.4 \cdot 10^3$ items/km$^2$) (Lebreton et al., 2018) and was measured for plastic trapped within hyacinths. Overall, this comparison between river and ocean plastic densities supports the hypothesis that most plastics is retained in rivers and not emitted into the oceans (van Emmerik, Mellink, et al., 2022). We also show that within rivers, aquatic floating vegetation such as hyacinths act as physical traps of floating plastics, accumulating even higher densities of plastics than otherwise found at the river surface.

Table 3: Floating transport and plastic densities estimates. We here report absolute values for floating plastic transport, irrespective of the flow direction.

**Floating transport**

| | Item transport | | Mass transport | | | |
|---|---|---|---|---|---|---|
| | [items/year] | | Mean mass/item [tonnes/year] | | Median mass/item [tonnes/year] | |
| Location(s) | Median | Mean | Median | Mean | Median | Mean |
| L1 | 90 | 109 | 903 | 1098 | 386 | 469 |
| L2 | 243 | 372 | 2447 | 3740 | 1045 | 1598 |

**River surface plastic density**

| | Item density | | Mass density | | | |
|---|---|---|---|---|---|---|
| | [items/km$^2$] | | Mean mass density [kg/km$^2$] | | Median mass density [kg/km$^2$] | |
| Location(s) | Median | Mean | Median | Mean | Median | Mean |
| L1 | $2.4 \cdot 10^4$ | $2.5 \cdot 10^4$ | 239 | 250 | 102 | 107 |

**Hyacinth plastic density**

| | Item density | | Mass density | | | |
|---|---|---|---|---|---|---|
| | [items/km$^2$] | | Mean mass density [kg/km$^2$] | | Median mass density [kg/km$^2$] | |
| Location(s) | Median | Mean | Median | Mean | Median | Mean |
| L1 | $1.8 \cdot 10^5$ | $2.1 \cdot 10^5$ | 1830 | 2107 | 782 | 900 |

### 3.2 Temporal variability in hyacinth abundance and plastic accumulation and transport

All variables related to hyacinth abundance, plastic densities and transport have a clear seasonality, with higher hyacinth and plastic loads during the dry season (Dec-May), compared to the wet season (Jun-Nov) (Fig. 3). Only for the river surface plastic density no significant statistical difference was found between dry and wet seasons (p-value=0.14); however, the mean river surface plastic density was 1.3 times higher during the dry season compared to the wet season (mean river surface plastic density for the dry and wet seasons, respectively: $2.8 \cdot 10^4$ items/km$^2$ and $2.1 \cdot 10^4$ items/km$^2$). Plastic transport variables (Fig. 3 E-H) have stronger significant values compared to metrics related to hyacinth abundance and plastic densities, especially for the site L2 (downstream location). This study monitored hyacinth coverage at one location over the river (L1, upstream location), but results are consistent with other studies that considered a larger geographic area. Janssens et al. (2022) characterized hyacinth abundance over a larger portion (115 km of river length and 12,64 km$^2$) of the Saigon river and showed that the dry season corresponds to higher water hyacinth abundance. Hyacinth coverage is the variable with the strongest correlation with plastic transport (Spearman $\rho$=0.86, p-value<0.05 for both L1 and L2) at a monthly scale (Table 4). Plastic densities were not found to be significantly correlated with plastic transport at a monthly scale. However, the Spearman correlation coefficients were found to be quite high and p-values close to significance level (all p-values<=0.2 and $\rho$>=0.46), suggesting that such a relation might exist but is not highlighted with the current data at a monthly scale, probably due to the relatively short time-series. Plastic densities were found to be significantly correlated with the number of hyacinth patches (Spearman $\rho$=0.82, p-value<0.05 and Spearman $\rho$=0.68, p-value<0.1 for hyacinth and river surface plastic density, respectively) but not with hyacinth coverage at a monthly scale (p-value>0.1). This highlights that high hyacinth plastic density values typically coincide with a high number of patches, but not necessarily with large hyacinth coverage.

The monthly time-series provide a more detailed view of the seasonal cycle in hyacinth coverage, plastic loads and transport throughout the year (Fig.4). The peak in plastic transport occurs between March and May (Fig.4 A-B): March for the seaward transport at the downstream site, May at the upstream site and April for landward transport at both locations. The highest plastic densities at the river surface and within hyacinths

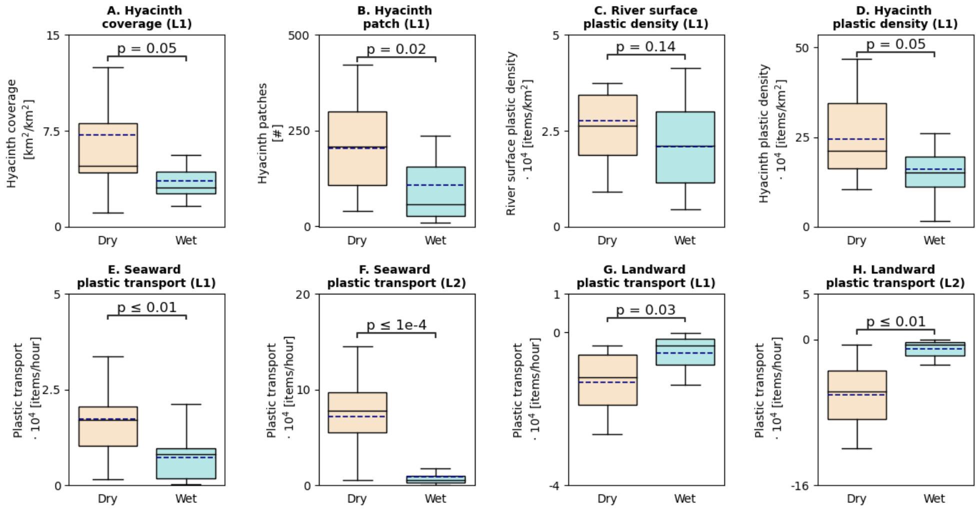


Figure 3: Seasonality at the Saigon river for A. Hyacinth coverage (L1) B. Hyacinth patch (L2). River surface plastic density (L1) D. Hyacinth plastic density (L1) E. Seaward plastic transport L2 F. Seaward plastic transport (L2). G. Landward plastic transport (L1). H. Landward plastic transport (L1). The blue dotted line indicates median values. Statistical differences between the dry (Dec-May) and wet (Jun-Nov) seasons were tested using the Krustal-Wallis test. p-values are indicated on top of each pair of boxplots. Values are considered statistically significant for p-value<=0.05.

Table 4: Spearman correlation coefficients between hyacinth abundance, plastic densities and transport variables. Variables were aggregated at both monthly and daily scales. Values marked with * indicate p-value<0.1, **< 0.05,***< 0.01. The absence of sign indicates p>0.1

| | Hyacinth coverage [km$^2$/km$^2$] (L1) | | Hyacinth patch [#] (L1) | |
|---|---|---|---|---|
| | Monthly | Daily | Monthly | Daily |
| River surface plastic density [items/km$^2$] (L1) | 0.64 | 0.36* | 0.68* | 0.02 |
| Hyacinth plastic density [items/km$^2$] (L1) | 0.32 | -0.29 | 0.82** | 0.41** |
| Plastic transport [items/hours] (L1) | 0.86** | 0.11 | 0.64 | 0.47** |
| Plastic transport [items/hour] (L2) | 0.86** | 0.08 | 0.43 | 0.38* |

| | River surface plastic density [items/km$^2$] (L1) | | Hyacinth plastic density [items/km$^2$] (L1) | |
|---|---|---|---|---|
| | Monthly | Daily | Monthly | Daily |
| Hyacinth coverage [km$^2$/km$^2$] (L1) | 0.64 | 0.36* | 0.32 | -0.29 |
| Hyacinth patch [#] (L1) | 0.68* | 0.02 | 0.82** | 0.41** |
| Plastic transport [items/hours] (L1) | 0.46 | 0.08 | 0.57 | 0.54*** |
| Plastic transport [items/hour] (L2) | 0.61 | -0.04 | 0.54 | 0.29 |

are registered during the month of February. This also corresponds to the month with the highest number of patches. Hyacinth coverage, on the other hand, is at its highest in March. It should be noted however, that variables for plastic densities and hyacinth abundance were not monitored during the month of April. Janssens et al. (2022) estimated hyacinth coverage over three years at the Saigon river, using satellite imagery. The time-series analysis showed that peaks in hyacinth typically occur between the end of February until the end of April. May and June mark the decline in all the variables studied. These months correspond to the start of the wet season over the Saigon river. For the year 2021, an increase in discharge and rainfall was observed starting from April and intensified from June onward (Supporting Information, Fig. S2). Few data were available between June and October, thus limiting our understanding of the full cycle of plastic loads over the wet season and the start of the post-monsoon season (Nov-Dec). van Emmerik et al. (2019)) observed a peak in plastic transport in September and October, based on observations conducted in 2018. Such a peak was not observed in the present study, despite the absence of data in August and September. The following months (Oct-Dec) generally correspond to an increase in all studied variables compared to the previous months (Jun-Sep). Overall, the monthly variations in plastic transport, densities and hyacinth coverage show similar trends but are not strictly synchronous. The noted discrepancies could result from gaps in data collection. However, they could also indicate a temporal lag between the different processes of plastic accumulation and transport.

At at a daily scale, hyacinth coverage and plastic transport are not significantly correlated for both upstream and downstream locations (p-value$>$0.01) (Table 4). No significant correlations were found between river surface plastic density and plastic transport for daily values either. Positive and statistically significant correlations were however found for other variable combinations. Hyacinth plastic density (L1: Spearman $\rho$=0.54, p¡0.01) and hyacinth patch quantities (L1: Spearman $\rho$=0.47, p-value$<$0.05, L2: Spearman $\rho$=0.38, p-value$<$0.01) have significant and positive relations with plastic transport for one or both monitored locations at a daily scale. One reason for the absence of correlation at daily scale between hyacinth coverage and plastic transport might be related to a temporal lag in the processes of hyacinth abundance and plastic transport. Fig.5 A and B detail the time-series of plastic transport, hyacinth coverage and river surface plastic density at L1 for two periods (March and May-June 2021). Both time-series clearly show first a peak in plastic transport, followed a few days later by an increase in hyacinth abundance and plastic densities (hyacinth coverage and river surface plastic density). In March, the peak in hyacinth coverage and plastic densities is asynchronous, with hyacinth coverage increasing 5 days before the highest river plastic density is observed. This is not the case for the period of May-June, where the peaks are registered on the same day. A likely explanation for this time lag between the transport and accumulation processes pertains to the succession of mobilization and retention processes. We hypothesize that high river discharge first mobilizes floating materials (including plastic and hyacinths), which get transported within the river system. Then, reduced water flows (probably due to tidal dynamics and/or seasonality in the net discharge) can cause a decrease in observed plastic transport for the same considered location. Simultaneously, low flow velocities cause the accumulation of plastic and hyacinths in certain parts of the river channel, for instance on its lateral sections. At L2 (downstream location), additional plastic inputs from the HCMC canals could also contribute to increased plastic densities in low flow conditions. Plastic densities and hyacinth abundance increase on the lateral sections of the river; until an increase again in discharge flushes the deposited debris again.

Overall, plastic transport, plastic densities and hyacinth abundance are closely linked. With few exceptions, all the variables studied show a correlation with plastic transport either at a daily or monthly scale. For certain variables (e.g.: hyacinth coverage and river surface plastic density), the temporal lag observed in transport and accumulation processes demonstrates that plastic transport is best predicted when considering a wider time-frame than the daily scale. Satellite images are not available at a daily resolution with sufficiently high spatial resolution to detect hyacinths in rivers. Hyacinth coverage can be estimated with freely available satellite imagery every 5 to 7 days (Janssens et al., 2022) for the same location. This allows to build reliable monthly hyacinth coverage estimates, making it a suitable proxy for plastic transport and accumulation in the Saigon river. The current observations indicate that monthly means in hyacinth coverage can be a good predictor of plastic transport.

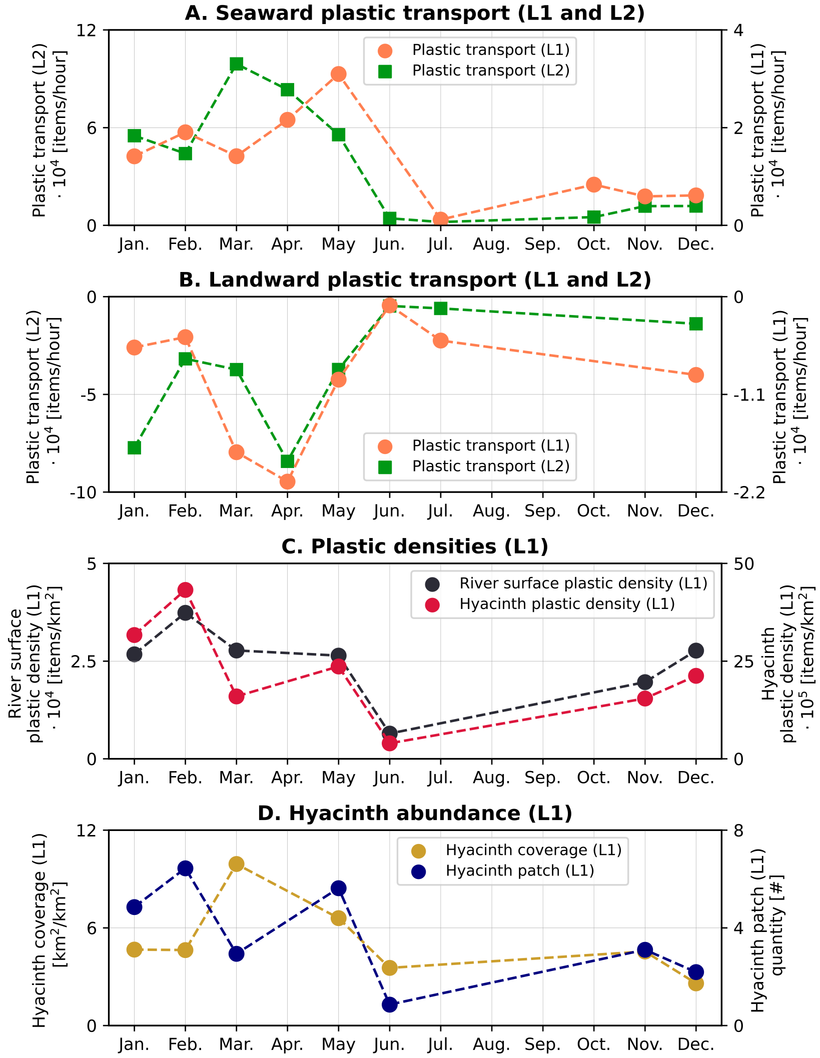


Figure 4: Monthly averages of variables related to plastic transport (A-B), plastic densities (C) and hyacinth abundance (D)

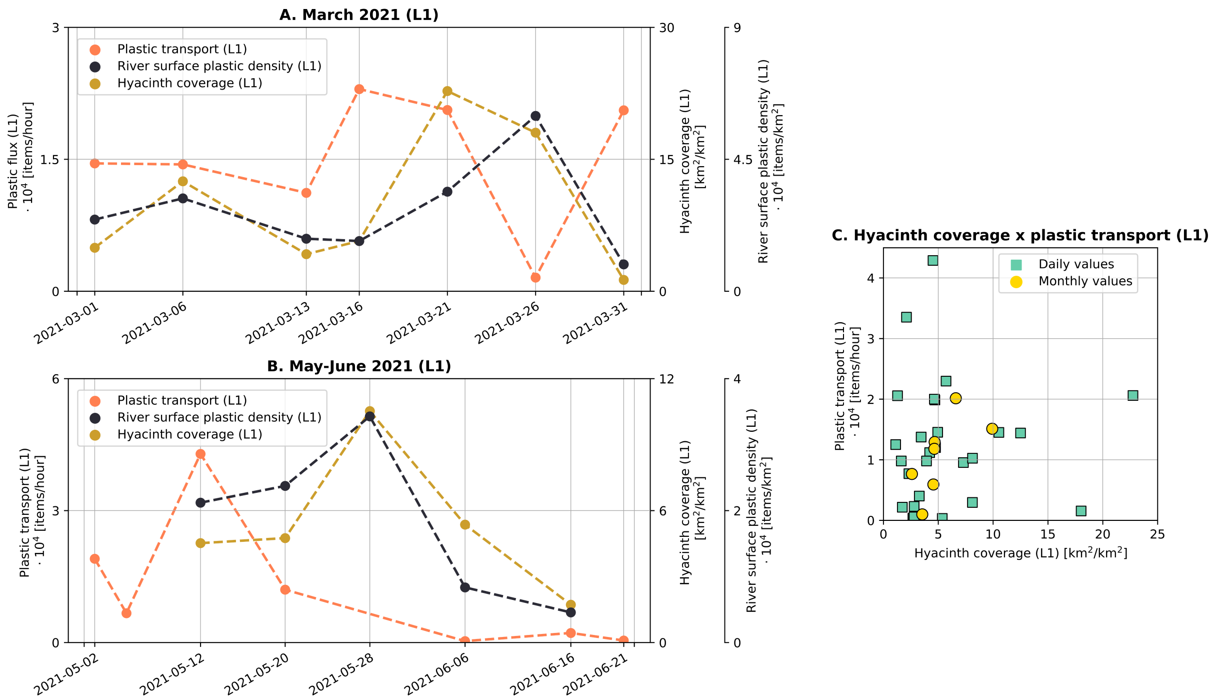


Figure 5: Observed daily values in hyacinth coverage, plastic transport and river surface plastic density at L1. A. Detailed time-series for the month of March 2021. B. Detailed time-series for the period of May-June 2021. C. Hyacinth coverage versus plastic transport at L1, daily and monthly mean values (Spearman $\rho = 0.11$ and 0.86, respectively, p-values>0.1 and <0.05).

### 3.3 Spatial variability in hyacinth abundance, plastic densities and plastic transport

Plastic transport are approximately 3 to 4 times higher at L2 (downstream) than at L1 (upstream). On average, the seaward transport is estimated at 4.4 $\cdot 10^4$ items/hour for L2 and 1.4 $\cdot 10^4$ items/hour for L1. The average landward plastic transport is -4.9 $\cdot 10^4$ items/hour for L2 and -1.0 $\cdot 10^4$ items/hour for L1. This difference in plastic transport between locations could be explained by additional quantities of plastic inputted between the monitored locations, a likely factor given that the river passes through Ho Chi Minh City's urban area. In addition, stronger tidal influence at L2 compared to L1 probably limits net discharge and net plastic transport, thus increasing plastic transport found in the water regardless of additional plastic inputs between monitored locations. Our current data did not quantify tidal dynamics and its effects on plastic transport, but lower net plastic transport can be expected at L1 given its more upstream position in the river.

Plastic densities were not monitored during this study at L2, but we compared our results for L1 with data from a previous study that reported such values for the same month (May). Similarly to this study, Schreyers, van Emmerik, Luan Nguyen, Phung, et al. (2021) used UAV imagery to estimate river surface plastic density, hyacinth plastic density and hyacinth patch size. These estimates were done only for the month of May 2020 at L2, which we compare with the L1 values found for May 2021. At L2, hyacinth plastic density was estimated at 2.1 $\cdot 10^6$ items/km$^2$. In this study, we found a value of one order of magnitude lower at L1 (2.4 $\cdot 10^5$ items/km$^2$, average for May 2021) than L2. River surface plastic density was also found to be higher at L2 (5.0 $\cdot 10^5$ items/km$^2$) compared

Table 5: Plastic transport, densities and hyacinth coverage at L1 and L2. (1) indicates values from Schreyers, van Emmerik, Luan Nguyen, Phung, et al. (2021). (2) indicates values from Janssens et al. (2022). In the latter, hyacinth coverage was monitored along several large reaches of the Saigon river using satellite imagery. Two of the monitored section include L1 and L2. Plastic densities and average hyacinth patch size are reported for the month of May 2021 for this study and May 2020 to allow comparison across studies. Hyacinth coverage values are here reported as the average over a 3-year time-series.

| | Seaward plastic transport [items/hour] | Landward plastic transport [items/hour] |
|---|---|---|
| L1 | $1.4 \cdot 10^4$ | $-1.0 \cdot 10^4$ |
| L2 | $5.0 \cdot 10^4$ | $-4.5 \cdot 10^4$ |
| | **River surface plastic density [items/km$^2$]** | **Hyacinth plastic density [items/km$^2$]** |
| L1 | $2.5 \cdot 10^4$ | $2.2 \cdot 10^5$ |
| L2 | $5 \cdot 10^5$ (1) | $2.1 \cdot 10^6$ (1) |
| | **Average patch size [m$^2$]** | **Hyacinth coverage [km$^2$/km$^2$]** |
| L1 | 1.5 | $1.4 \cdot 10^1$ (2) |
| L2 | 0.82 (1) | $9.5 \cdot 10^{-2}$ (2) |

to L1 ($2.6 \cdot 10^4$ items/km$^2$). The higher plastic densities found at L2 confirm that larger riverine plastic quantities are present downstream. The increase in hyacinth plastic densities downstream can also be partially explained by a decrease in hyacinth coverage between L1 and L2. Janssens et al. (2022) estimated hyacinth coverage continuously for three years (2018-2020) over a large portion of the Saigon river, including the two locations of this study. Between 2018 and 2020, on average, the midstream section (where L1 is situated) had approximately 15 times larger hyacinth coverage than the downstream area (where L2 is located). In addition to a decrease in hyacinth coverage, hyacinth patches are also of a smaller size downstream than upstream. Schreyers, van Emmerik, Luan Nguyen, Phung, et al. (2021) estimated hyacinth patch average size at L2 at 0.82 m$^2$ in May 2020. In this study, we found that hyacinth patches were on average twice as large in size at L1 (size of 1.5 m$^2$, average for May 2021). This decrease in hyacinth patch size is likely the result of mechanical break-down due to boat traffic and possibly higher flow velocities (Petrell & Bagnall, 1991). This comparison across studies bears many uncertainties, mainly because it assumes that the temporal variation in hyacinth and plastic densities is negligible between May 2020 and May 2021. Given the high temporal variability in plastic densities observed in this study, and the intrannual variability in hyacinth coverage found in Janssens et al. (2022), such an assumption is probably incorrect. For instance, between 2018-2020, hyacinth coverage was found to vary by as much as a factor of eight for the month of May (Janssens et al., 2022). This factor however, remains much lower than the difference found in hyacinth coverage between L1 and L2 (of a factor of 15). We can therefore reasonably infer that hyacinth coverage decrease and plastic transport and densities increase along the river course still holds. Upstream of Ho Chi Minh City, hyacinth can cover a large extent of the river surface, up to 24% of the river surface (Janssens et al., 2022). As the hyacinth drift downstream of the city, patches get destabilized and break-down into smaller patches. Overall, the hyacinth coverage decreases, covering on average less than 0.1% in its most downstream section. Conversely, the plastic densities at the river surface and within hyacinth are higher downstream than upstream of Ho Chi Minh City. The higher quantities in plastic result in higher plastic transport downstream than upstream of the city.

In addition to spatial variation between upstream and downstream locations, the horizontal spatial variability (i.e.: across the river width) is also an important factor to understand the nexus between hyacinth abundance and plastic accumulation and transport processes. Overall, we did not find that plastic densities, plastic transport and hyacinth abundance all followed a similar horizontal spatial distribution (Fig. 6 A-B). Our findings show that high transport of plastics can coincide with both high hyacinth coverage, which occurs in the lateral reaches of the river; or with low hyacinth coverage in the middle of channel. Our observations suggest that the drivers for these two high transport modes are of different nature. The first is mainly driven by the mobilization of hyacinth patches, the second is more closely tightened to variations in flow velocities and plastic quantities found in the river.

Hyacinths tend to accumulate on the sides of the river channel, where the flow velocity is lower. Both the coverage and number of patches gradually decrease towards the middle of the river channel (Fig. 6A). River surface plastic density follows a similar distribution (Fig. 6B) and was found to be positively correlated with hyacinth abundance (hyacinth coverage:$\rho$=0.84, p-value$<$0.01, hyacinth patch: $\rho$=0.47, p-value$<$0.05). A peak in river surface plastic density was however observed at 80 m from the West bank, in a section of the river with low hyacinth coverage ($<$4% on average). Hyacinth plastic density and plastic transport, on the other hand, have a more complex and chaotic spatial distribution, with a succession of peaks and drops in values (Fig. 6B). An overall trend is difficult to establish. No strong significant correlation was found between these variables and hyacinth abundance, or among themselves (all $\rho<0.2$). For plastic transport, two main areas where high plastic transport typically occur can be distinguished. One is at around 25 m from the West riverbank, in an area with generally high hyacinth coverage and high plastic densities. Plastic transport is also relatively high at approximately 120 m from the West riverbank, in an section with low hyacinth coverage. The discrepancies in the spatial distribution of plastic densities is explained by the fact that one considers the river area as its reference, and the other the hyacinth coverage. High hyacinth plastic densities can be observed in areas with low surface plastic densities and hyacinth abundance, notably in the case of high quantities of plastic present in small hyacinth patches. Overall, we can distinguish four modes of transport and accumulation across the river (Fig. 6C). On both lateral sides of the river channel high coverage of hyacinth dominates. This high accumulation is combined with both low and high transport rates. Both hyacinth and plastic tend to accumulate in this area, due to low current velocities. When the current increases, hyacinths get mobilized in batches and important quantities of plastic and hyacinth are then washed out, resulting in high plastic transport. On the lateral reaches of the river, plastic transport is therefore intermittent, alternating periods of low plastic transport and high accumulation (deposition dominated) with 'washed-out' periods (transport dominated). One main unknown is the thresholds in flow conditions (stream velocity and water level) necessary to destabilize these temporary deposition zones. In the middle reach of the river channel, both high and low plastic transport rates can be found as well, hyacinth coverage is generally low. Hyacinth patches do not cover large portion of the river surface there, are highly mobile and generally present in small amount.

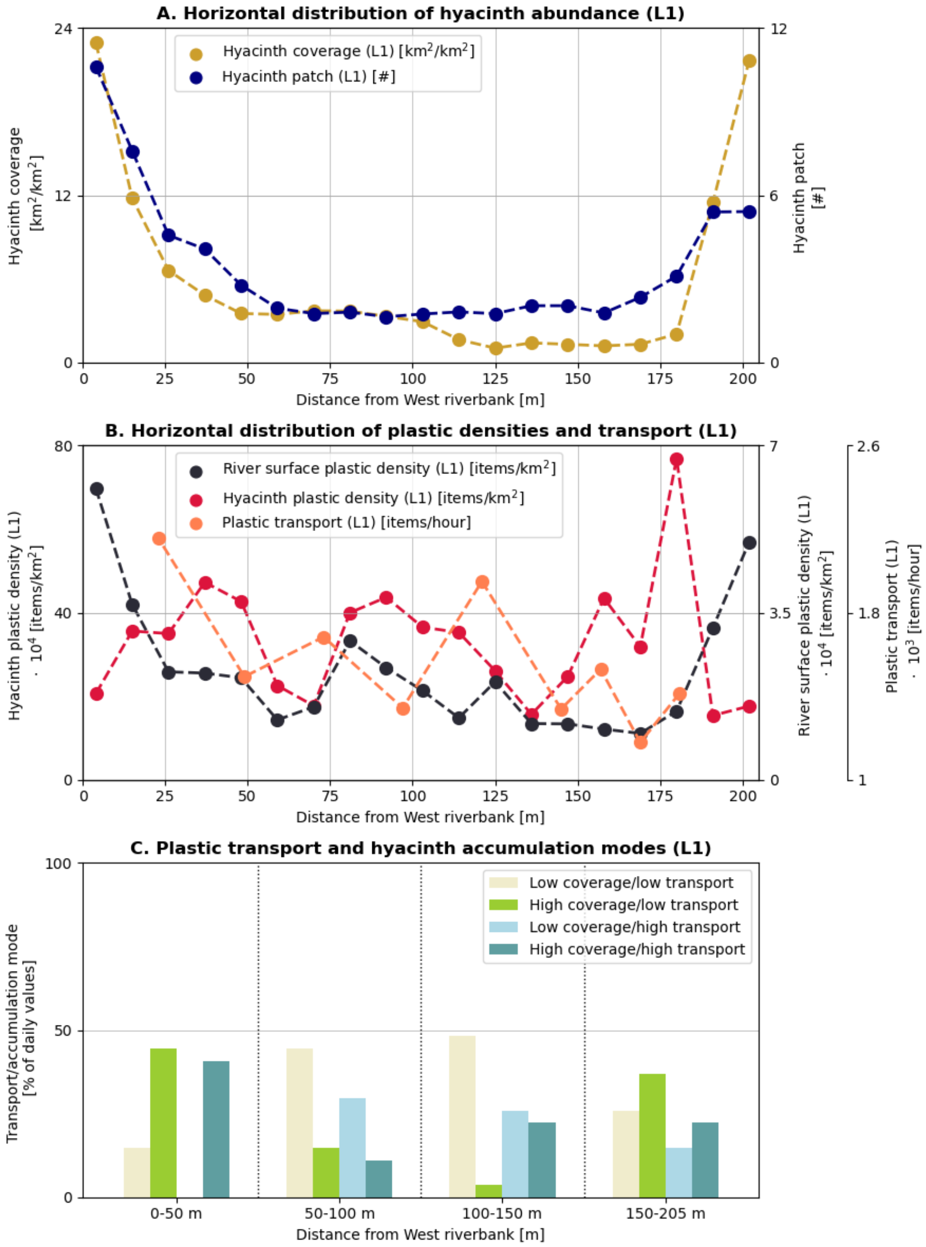


Figure 6: Horizontal distribution of hyacinth abundance (A) and plastic densities and transport (B) Plastic transport / hyacinth accumulation modes (C). Daily values were averaged across the river section.

# 4 Synthesis and Outlook

## 4.1 Summary

In this study, we demonstrated the role that hyacinths have in accumulating and transporting floating plastic. We found that $\sim 60\%$ of transported items are trapped within hyacinth patches, and that hyacinth plastic densities are on average one order of magnitude higher than otherwise found at the river surface. In comparison, the highest plastic densities found in the Great Pacific Garbage Patch are 190 times lower. Hyacinths function as major temporary sinks for floating plastics; however this trapping effect varies greatly both in time and space. Our analysis showed that on a temporal scale, high plastic transport and hyacinth coverage tend to co-occur, especially when considering a monthly to seasonal scale. This is likely the result of a time-lag between plastic transport and hyacinth coverage peak events at a sub-monthly scale. Plastic densities, hyacinth coverage and plastic transport are all higher during the dry season (Dec-May) when compared with the wet season (Jun-Nov) At a spatial scale, we identified different transport modes in relation to hyacinth coverage. Depending on the sections of the river, different mechanisms can explain high plastic transport rates. In the lateral sections of the river, low surface flow velocities and the abundance of high hyacinth coverage promote the temporary deposition of large quantities of items, with limited transport rates (Fig. 7A). Increased surface flow velocities mobilize in batches of these temporary accumulation zones, leading to high plastic transport rates (Fig. 7B). In the middle of the channel, plastic items are less affected in their trajectories by hyacinth-water interactions, and move therefore more freely at the water surface. We hypothesize that the intermittent transport on the lateral reaches of the river is mainly governed by semi-diurnal variations in river flow, caused by tidal dynamics.

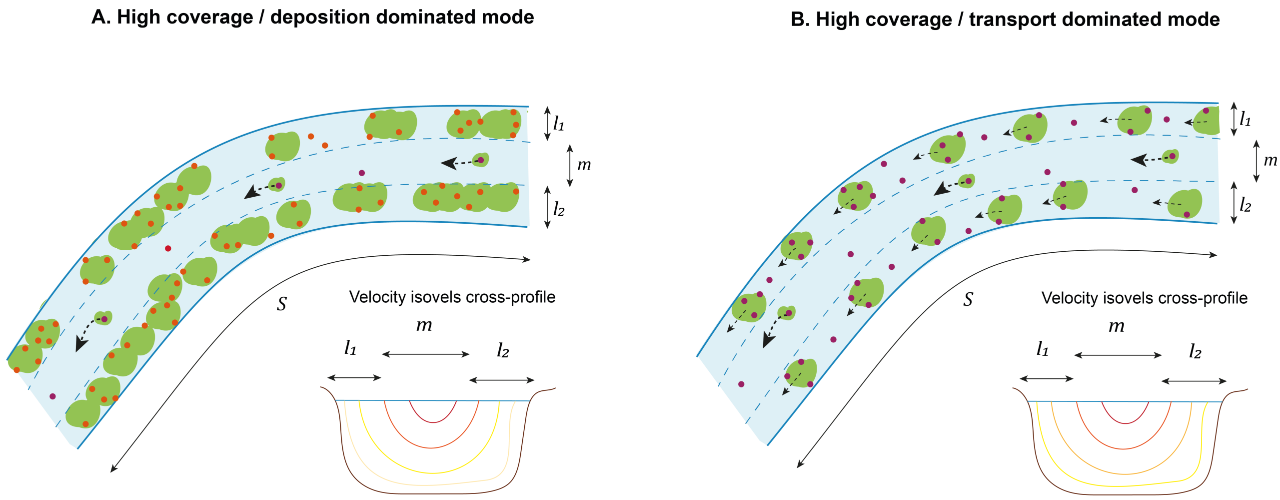


Figure 7: Variation in plastic transport modes on the lateral reaches of the river channel depending on hyacinth coverage. A. Deposition dominated mode, hyacinths and plastic have limited mobility during low flow conditions. B. Transport dominated mode, the hyacinths and plastic are mobilized in batches. $S$ is the total longitudinal section of the river considered, $l_1$ and $l_2$ correspond to the lateral sections of the river, and $m$ signifies the middle section. The cross-sectional views schematize the velocity isovels, with lower flow velocity on the lateral section of the river during a deposition dominated mode.

### 4.2 Conceptual model for plastic-hyacinth interactions

Fluvial plastic transport is affected by several hydro-meteorological and ecological factors (Schreyers, van Emmerik, Luan Nguyen, Castrop, et al., 2021; Hurley et al., 2018; Roebroek et al., 2021; van Emmerik, de Lange, et al., 2022) (Fig. 8A), of which hyacinth coverage is a key component for tropical rivers. Low rainfall rates during the dry season both limit freshwater discharge (Fig. S2) and net plastic transport, but generate an increase in hyacinth coverage (Camenen et al., 2021; Harun et al., 2021; Janssens et al., 2022). This is likely the result of the higher nutrient concentrations found in the water during periods of low net river discharge. In turn, increased hyacinth coverage also alters plastic transport, with high rates of (temporary) deposition within hyacinths. In-stream vegetation (floating and submerged) can function as a resistance force to water flows in certain systems (Wharton et al., 2020; Sand-Jensen, 1998; Cornacchia et al., 2020) and ultimately regulate surface flow velocities and water levels. We hypothesize that because of this influence on the riverine flow dynamics, high hyacinth abundance also affects fluvial plastic transport, by causing a (temporary) trapping of items, thus ultimately decelerating transport transport. During the wet season, the lower coverage of hyacinths results in lower deposition/accumulation rates of plastic items within patches compared to the dry season. The role of hyacinths as aggregators and temporary sinks is therefore more limited during this season. The fate of plastic could be affected by this in two distinct ways. Items could flow more freely at the water surface, probably leading to longer transport trajectories. Another likely scenario is that limited hyacinth coverage facilitates the contact and deposition of plastic in other compartments, such as riparian vegetation or riverbanks. In such a case, the higher hyacinth abundance during the dry season can be considered as a barrier to other accumulation processes. Plastic deposition in these compartments would probably result in longer deposition periods, because they can be considered more stable (e.g. less frequently affected by hydrological dynamics).

The above-mentioned interactions between hyacinth coverage, plastic densities and net discharge affect the seasonality in plastic transport (Fig. 8B). We can distinguish three phases in the annual plastic transport cycle: an accumulation phase, a flushing phase and a baseflow phase. The accumulation phase corresponds to the bulk of the dry season (Dec-Mar). During this phase, the Saigon's net discharge is low, with even negative net discharge monthly values registered for some years (Camenen et al., 2021). Net discharge estimates were not available for the year 2021. However, measured freshwater discharge and rainfall rates in 2021 also suggest low net discharge rates for the period spanning from December to March (Fig. S2). In this accumulation phase, plastic densities are gradually increasing due to the cumulative effect of additional plastic inputs and limited net downstream plastic transport. Most plastics therefore remain into the river, moving upstream and downstream depending on the flow direction. High total plastic transport rates are observed, mainly governed by the high plastic densities found in the river. A large part of the transported items are most likely not flushed out of the system, because of the relative low net discharge.

At the beginning of the wet season (Apr-Jun), the increased net discharge generates a flushing effect (Fig. S2). Most items are transported downstream and plastic densities in the river channel therefore decrease. Higher flow velocities destabilize hyacinths, which tend to break-down more easily. Other studies also observed that increased precipitation rates can be associated with the seasonal reduction in hyacinth coverage during the wet season (Janssens et al., 2022; Harun et al., 2021). During the wettest months (Jul-Nov), rainfall levels, freshwater discharge (Fig. S2) and thus net discharge (Camenen et al., 2021) are at their highest. However, plastic transport rates are low during this period, as a result of a drop in plastic densities during the previous flushing phase (baseflow phase).

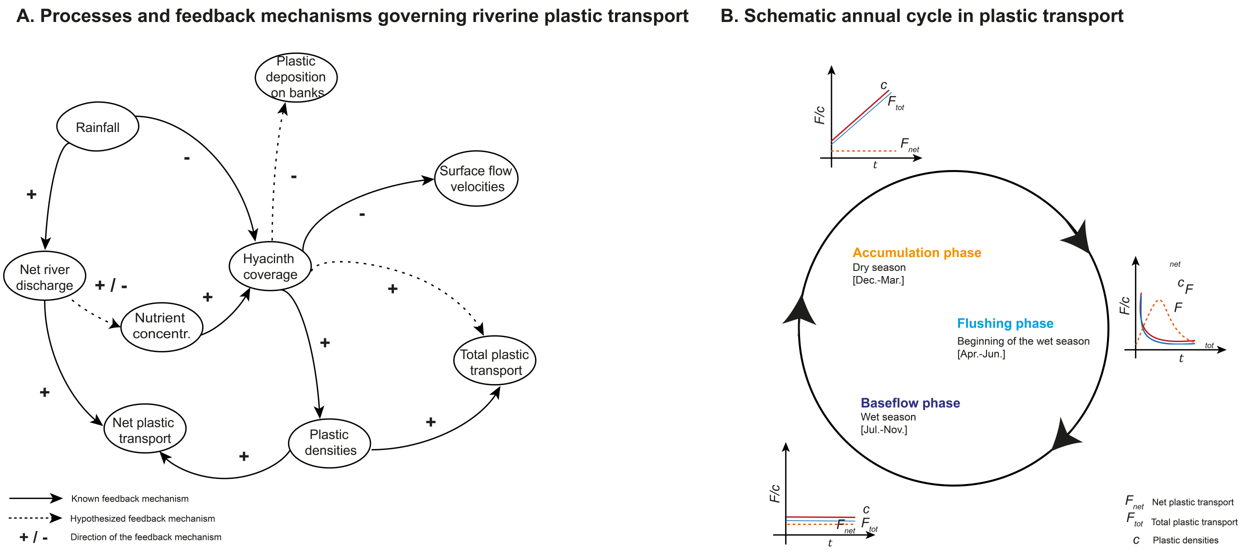


Figure 8: Overview of plastic transport processes in the Saigon river, under the assumption of constant plastic influx. A. Processes and feedback mechanisms governing riverine plastic transport B. Schematic annual cycle in plastic transport.

## 4.3 Discontinuity in plastic transport

This study confirmed that hyacinths alter fluvial plastic transport by generating discontinuous effects at various levels. The majority of plastics are trapped by hyacinths (∼60%), despite hyacinth only covering ∼6% of the river surface, thus confirming the role of hyacinths as major accumulators of plastics (*physical discontinuity*). The fate of plastic transport in rivers is therefore impacted not only by water-particle interactions but also by the interactions with floating vegetation. As a result, the presence of hyacinths generates different transport modes, with different accumulation and release dynamics between areas where hyacinth are abundant and less affected areas. For instance, an intermittent transport mode was observed on the lateral sections of the river (*spatial discontinuity*). In addition, the seasonality in net river discharge similarly affects both hyacinth coverage and plastic transport. In the accumulation phase, high hyacinth coverage alters the temporary deposition and release dynamics of plastics, because items are more often and more likely temporarily deposited and released by hyacinths. Without such large hyacinth coverage, the deposition mechanisms of plastic would likely be dominated by interactions with the banks, with seasonal release timescale, whereas transport mechanisms would be entirely governed by daily flow dynamics (*temporal discontinuity*).

## 4.4 Outlook

For tropical river systems heavily affected by tidal influence and seasonal variation in river net discharge, such as the Saigon river, distinguishing between net and total plastic transport is essential. Estimating the net plastic transport is however challenging, as it requires to take into account: a) ebb and flood phases during the semi-diurnal tidal cycles; b) neap and spring tides, and c) annual net discharge cycle. The net transport of items over a river longitudinal section can be expressed as the product of seaward and landward plastic transport within a predetermined area. Factors affecting the variation between seaward and landward transport include tidal dynamics, variations in freshwater discharge and the resulting seasonality in net water discharge, as well as deposition mechanisms in other river compartments.

Current observation techniques and protocols are limited in time and space, and do not enable accurate quantification of net plastic transport in rivers. The timescales of observations are inappropriate to estimate plastic mobility, especially in systems with fluctuating transport regimes such as tidal rivers, and systems heavily affected by temporary deposition mechanisms (for instance due to high floating vegetation presence). For our observations, both landward and seaward plastic transport were considered, but monitoring was not carried throughout entire tidal cycles and thus we could not accurately quantify net plastic transport. Continuous measurements throughout tidal cycles are needed to further characterize plastic mobility in rivers. Techniques such as tracking of the mobility of individual particles, for instance with GPS trackers (Ledieu et al., 2022; Newbound, 2021; Tramoy et al., 2020) and continuous transport measurements over tidal cycles could help in better understanding plastic transport mechanisms.

Despite characterizing hyacinths as temporary sinks of plastics, we could not quantify deposition times of plastics within hyacinths, nor do we know the hydraulic conditions at which accumulations of hyacinth-plastic are entrained. This aspect is particularly important as it likely determines the alternation between mobile and relatively stable phases of hyacinths-plastic mobility and ultimately affects the timescale of fluvial plastic transport. Furthermore, to better understand the overall role of hyacinths as temporary sinks of plastics and how this relates to other components of the river system, studies on transport and temporary deposition mechanisms across various riverine compartments are needed. Extending direct observations is one way forward, but presents certain challenges. First, it is usually time consuming and can sometimes be costly. Second, isolating the explaining variables is often challenged by the inherent complexity and heterogeneity of the observed systems. Another way forward could involve testing hypothesis on deposition and transport dynamics of plastic within vegetation and other sinks through controlled laboratory experiments. This could be done for instance by building physical models that test under which hydraulic conditions floating plastics are mobilized and deposited in various river compartments. Nevertheless, extending field-based research to other tropical systems is a necessary step to further explore the role of hyacinth in trapping and transport plastics.

## 5 Conclusions

Hyacinth function as a major temporary sink for riverine floating plastics. Plastic densities in hyacinths were found to be 10 times higher than at the river surface and $\sim$ 60% of the total transported items were trapped by hyacinth patches. These plant-plastic dynamics are not unique to the main observation location, as similar findings were also found for another location in the Saigon river. This suggests that the results are transferable to other sites within the river, as well as to other fluvial systems invaded by hyacinths.

Temporally, peaks in plastic transport and hyacinth coverage coincide, especially on a monthly to seasonal scale. A time-lag in peak events was observed at a sub-monthly scale. These findings suggests that to a certain extent, hyacinth coverage could be used as a proxy for plastic pollution. In addition, we showed that hyacinths are a key component in explaining plastic transport mechanisms. Peaks in plastic transport are caused either by high transport governed by daily flow dynamics - mainly in the middle of the channel -, or by high accumulation of hyacinth-plastics in the lateral sections of the river, which can be mobilized in batches.

We linked hyacinth coverage and plastic accumulation to hydrological factors in a conceptual model, which can be used to explain spatio-temporal variations in plastic transport. A crucial aspect is the distinction between net and total river discharge, which likely drives changes in net/total plastic transport and hyacinth coverage at the river scale. We identified three phases (accumulation, flushing, baseflow phases) throughout the year which explain the annual variation in net and total plastic transport within the river.

Overall, hyacinth abundance in tropical rivers alters floating plastic transport because it interferes with the two-way interaction between water and plastic items. Because they trap the majority of plastic items, the mechanisms driving hyacinth movement and temporary deposition at the river surface also influence plastic propagation in rivers. As major temporary (and mobile) sinks of plastics, hyacinth abundance lead to increased discontinuity in plastic transport.

## 6 Data availability

All the UAV images used in this study are publicly available at https://doi.org/10.4121/21648152.v1. All remaining data will be made publicly available upon publication and have been included in the submission documents.

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# Discontinuity in fluvial plastic transport increased by floating vegetation

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**Key Points:**

- Water hyacinths are major plastic sinks, with plastic densities up to ten times higher than at the river surface.
- Plastic transport, plastic densities and hyacinth abundance are closely linked, with timing and location of accumulation coinciding.
- Hyacinth coverage and plastic densities are affected by fluctuations in river discharge which in turn impact plastic transport seasonality.

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## Abstract

Understanding plastic mobility in rivers is crucial in estimating plastic emissions into the oceans. Most studies have so far considered fluvial plastic transport as a uniform process, with stream discharge and plastic concentrations as the main variables necessary to quantify plastic transport. Decelerating (e.g.: trapping effects) and accelerating effects (e.g.: increased water flows) on plastic transport are poorly understood, despite growing evidence that such mechanisms affect riverine plastic mobility.

In this observation-based study, we explored the roles of an invasive floating plant species (i.e. water hyacinths) as a major disruptor of plastic transport. The different functions of aquatic vegetation in trapping and transporting plastics play a key part in our evolving understanding of how plastic moves in rivers. We collected a one-year dataset on plastic transport, densities and hyacinth abundance in the Saigon river, Vietnam, using both a visual counting method and UAV imagery analysis.

We found that hyacinths trap the majority of floating plastic observed ($\sim$60%), and plastic densities within patches are ten times higher than otherwise found at the river surface. At a monthly and seasonal scale, high hyacinth coverage coincides with peaks in both plastic transport and densities over the dry season (Dec-May) in the Saigon river.

We also investigated the large-scale mechanisms governing plant-plastic-water interactions through a conceptual model based on our observations and available literature. Distinguishing total and net plastic transport is crucial to consider fluctuations in freshwater discharge, tidal dynamics and trapping effects caused by the interactions with aquatic vegetation and/or other sinks.


## 1 Introduction

Plastic pollution poses a series of threats to global ecosystems, including aquatic systems such as rivers. High levels of plastic pollution in rivers can reduce availability of potable freshwater, cause damage to urban infrastructure, and potentially harm the local fauna (van Emmerik & Schwarz, 2020). Rivers are considered the main pathways for land-based plastic emissions into the oceans (Meijer et al., 2021). In addition, rivers can also retain plastics for decades, if not longer (Tramoy et al., 2020). Understanding plastic mobility in rivers is therefore crucial for risk assessments for riverine ecosystems under variable plastic concentrations, and for accurate estimations of emissions into the oceans.

Rivers have long been considered as simple conduits for plastic transport to the sea. Many studies portrayed the plastic journey in rivers to be a continuous trajectory of particles through a uniform medium that offers little to no resistance to its final export into coastal waters. As a result, plastic transport in rivers is often quantified as a direct function of plastic concentrations in the water and river discharge (Schmidt et al., 2017; van Emmerik et al., 2018; Haberstroh et al., 2021). However, recent scientific advances have shed light on the discontinuous dynamics at play in fluvial plastic transport; at both temporal and spatial scales. Temporally, plastic transport rates have been observed to follow seasonal patterns and transport in various rivers (van Emmerik et al., 2019; van Emmerik, de Lange, et al., 2022), at times linked to seasonal variation in freshwater discharge. In addition, extreme discharge events such as floods lead to disproportionally increased plastic transport rates (Hurley et al., 2018; Roebroek et al., 2021; van Emmerik, Frings, et al., 2022). Spatially, changes in river shape such as meander bends and the presence or absence of physical barriers can lead to varying trapping rates, which affects plastic propagation in the water (Newbound, 2021). Physical traps or barriers include infrastructure such as damns, groynes, bridges and weirs, as well as bank and aquatic vegetation. These impediments can physically retain plastic items temporarily or even permanently (Cesarini & Scalici, 2022; Schreyers, van Emmerik, Luan Nguyen, Castrop, et al., 2021; Skalska et al., 2020). In addition, varying plastic concentrations caused by human behaviours along the river (plastic leakage and removal) contributes to spatially varying plastic transport rates. These discontinuities likely lead to accelerating or decelerating effects of plastic distribution and propagation in the water, similarly to what is observed for other floating debris such as wood (Wohl, 2017; Wohl & Scott, 2017). As such, these discontinuities challenge the common assumption of a uniform and unidirectional effect of river discharge on plastic mobility.

Aquatic vegetation can disrupt plastic mobility in rivers physically, spatially and temporally, and could therefore generate discontinuous effects in fluvial plastic transport. Vegetation can trap plastic items, therefore leading to deposition and transport mechanisms that are affected by water-plant-plastic interactions (*physical discontinuity*). Vegetation coverage varies due to the seasonal cycle, which, in turn, leads to higher or lower plastic retention rates depending on the period of the year considered (*temporal discontinuity*). Small scale variations in vegetation abundance along and/or across a given river might also alter both plastic transport and deposition rates (*spatial discontinuity*). Here, we explore the discontinuous nature of fluvial plastic transport by focusing on the role of an aquatic vegetation species (e.g.: water hyacinths, *Eichhornia crassipes*) in trapping plastics in the Saigon River. Hyacinths function as a major aggregator of floating macroplastics in tropical rivers and can, therefore, act as a dominant control factor of fluvial plastic transport (Schreyers et al., 2021a; Schreyers et al., 2021b). These invasive aquatic species are now present in most tropical lakes and rivers worldwide (CABI, 2020; Thamaga & Dube, 2019), and their coverage of water surfaces can double in within one to two weeks due to their rapid growth rate (Ouma et al., 2005). As a surface plant species, hyacinth float in patches of varying sizes and densities. Their drift patterns are passive, and spatial distributions are influenced by factors such as currents and wind. In low flow conditions, hyacinths can rapidly blanket a large portion of the waterway. Kleinschroth et al. (Kleinschroth et al., 2021) found that for small reservoirs, peaks in hyacinth coverage often exceeded 80% of the total reservoir area. Conversely, in more active systems like rivers, hyacinth coverage tends to be lower due to the transport of the plants with water flow, but can still reach up to 25% of the river surface (Janssens et al., 2022). Previous field-based studies have successfully shown that hyacinths play a crucial role in fluvial plastic transport, however, these observations were conducted over a short measurement period (6 weeks) and at only one location. This study provides a much-needed more comprehensive understanding of how hyacinth abundance alters fluvial plastic transport over both time and space.

For the present study, we monitored hyacinth coverage, plastic transport and plastic densities in the Saigon river, Vietnam, over one year. The Saigon river has one of the highest plastic transport rates in the world and is severely impacted by hyacinths invasion (van Calcar & van Emmerik, 2019; Janssens et al., 2022). We hypothesize that hyacinths function as a major temporary sink for riverine plastics and that therefore temporal peaks and spatial accumulation zones in hyacinth coverage generally coincide with high plastic loads. We first established the overall role of hyacinths as temporary traps for plastic items (section 3.1). We then investigated the evolution of the measured metrics (e.g.: hyacinth coverage, plastic transport and densities) at various temporal scales (seasonally, monthly and daily) to characterize synchronous or asynchronous trends in transport and accumulation (section 3.2). In addition, we analyzed how these variables are spatially distributed in the river system, between upstream and downstream locations along the river and across the river channel (section 3.3). The first part of this study focuses on quantifying hyacinth's role as a temporary and mobile sink of floating plastic based on our field observations (section 3. Results and Discussion). In the second part, we further expand on the interactions between plastic-plant-water at a system scale (section 4. Synthesis and Conceptual model). We first summarize our main findings which identified different modes of plastic transport in the river in relation to hyacinth coverage (section 4.1). We present a conceptual model based on these observational findings and our broader understanding of the fluvial system investigated, to explain spatio-temporal variations in plastic transport (section 4.2). We thus synthesize the discontinuous effects induced by hyacinth abundance on plastic transport (section 4.3) and finally identify next steps in future research effort that seek to understand large-scale plastic transport and deposition processes in fluvial systems (section 4.4). The outcomes of this study are useful for scientists seeking to understand large-scale fluvial plastic transport and deposition mechanisms. In addition, river plastic monitoring and reduction strategies might seek to opportunistically use (temporary) sinks because of their role in aggregating large quantities in floating plastics.

# 2 Data and Methods

## 2.1 Study area

We measured plastic transport, hyacinth abundance and plastic densities between December 12, 2020 and January 15, 2022 at the Saigon river, Vietnam (Fig. 1 and Table 1). The Saigon river originates in Cambodia and flows into the Dau Tieng reservoir, approximately 120 km north from Ho Chi Minh City (Nguyen et al., 2020). The river crosses agricultural areas of paddy rice and rubber plantation before entering the city. South of the city, the Saigon river confluences with the Dong Nai river. There, the Dong-Nai-Saigon river system branches into several channels that meanders in the Can Gio mangrove forest before entering the East Sea (Dijksma et al., 2010). The Saigon river is subject to asymmetrical semi-diurnal tidal cycle. Because of the tidal influence, the net river discharge is considered relatively low and subject to seasonal variations between the dry and wet seasons (monthly averages vary between -80 and 320 $m^3/s$) (Camenen et al., 2021). In addition, the Saigon river is considered one of the most plastic polluted rivers worldwide, with transport rates within the order of $10^4$ items/hour (van Calcar & van Emmerik, 2019). Hyacinth invasions are also particularly severe in this river, with peak coverage reaching up to 14% of the river surface (Janssens et al., 2022).

This study focuses on floating macroplastic (>0.5 cm of size) density and transport, hereafter referred to as plastic. Plastic transport was measured at two locations in Ho Chi Minh City (Fig. 1). The first site (L1) is located north of the city (10.89025, 106.69209) and the second (L2) in its southern part (latitude: 10.785984; longitude: 106.718332). The two monitored sites approximately 30 km apart. At Ho Chi Minh City, the Saigon river progresses from north to south, therefore enabling to compare upstream and downstream plastic transport values within the urban area. Plastic transport was measured using the visual counting method for floating bridges from bridges (section 2.2), and hyacinth abundance and plastic density were measured using Unmanned Aerial Vehicle (UAV) imagery analysis (section 2.3 and 2.4). Flying at the downstream site was deemed unfeasible for long-term monitoring, due to the proximity of a military site. For this reason, UAV surveys were only conducted at L1. UAV images were taken across the river channel, with a frequency of one to four flights per measurement day. Each flight consisted of two overpasses across the Saigon river, with a range of 41 to 65 images taken per flight. UAV surveys were carried at a constant elevation of approximately 10 m above the water level. More information on the UAV surveys is available in Supporting Information (Extended Methods). Table 2 summarizes the measurement frequencies per month at each location. Data gaps are noticeable for certain months: no data could be collected for any of the variables investigated in August and September 2021. Due to the COVID-19 pandemic, a strict confinement was mandated in Ho Chi Minh City, thus not allowing observers to leave their houses. A larger data gap is noticeable for hyacinth abundance and plastic densities, with no measurements conducted in April, July and October 2021. The gap during the month of April was due to the unavailability of the observer conducting the UAV flights. The missing data from July and October 2021 was also caused by COVID-19 restrictions. In those months, the government did not allow inhabitants to cross the border between two different provinces, thus not enabling access to the UAV flying site at L1 (a few hundred meters upstream of where the visual counting measurements were conducted).

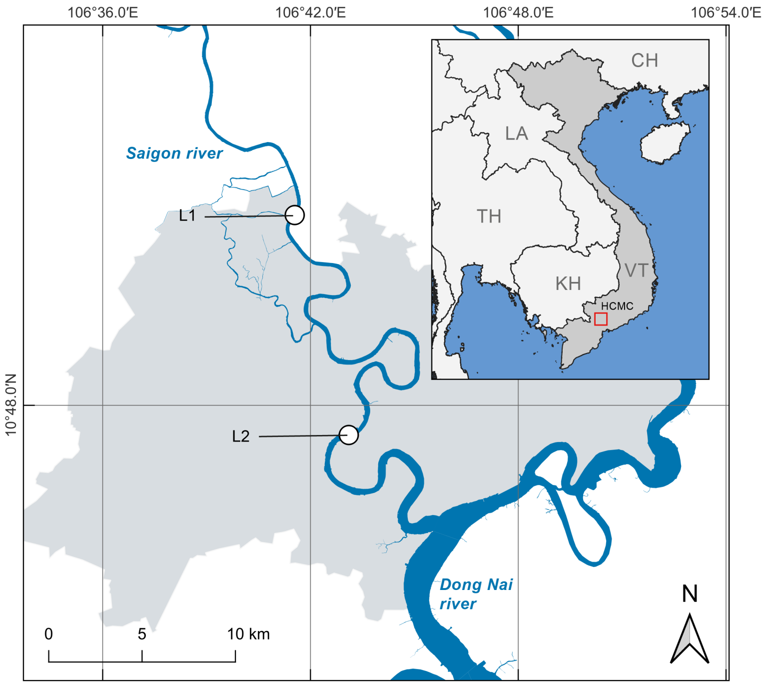


Figure 1: Localization map of monitored sites in Ho Chi Minh City (HCMC), Vietnam and measurement frequency at each location.

Table 1: Measurement frequency at each location. Total refers to the total number of UAV images analyzed in the case of hyacinth abundance and plastic densities. For plastic transport, it refers to the total number of observations, with one observation corresponding to a measurement per observation segment.

| | **Measurement locations** | | | |
|---|---|---|---|---|
| | L1 | | L2 | |
| | *Total* | *Daily* | *Total* | *Daily* |
| Plastic transport | 900 | 49 | 1,272 | 51 |
| Hyacinth abundance | 3,544 | 29 | N/A | N/A |
| Plastic densities | 2,360 | 29 | N/A | N/A |

Table 2: UAV images and plastic transport measurement frequency per month. The values here refer to the total number of UAV images for hyacinth abundance and plastic density. For plastic transport, the reported values correspond to the total number of observations. Blank cells indicate that no observations were conducted for that period.

| | Number of measurements by month | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dec 20 | Jan 21 | Feb 21 | Mar 21 | Apr 21 | May 21 | Jun 21 | Jul 21 | Aug 21 | Sep 21 | Oct 21 | Nov 21 | Dec 21 | Jan 22 |
| Plastic transport (L1) | 54 | 108 | 72 | 126 | 126 | 90 | 54 | 36 | | | 18 | 90 | 90 | 36 |
| Plastic transport (L2) | 84 | 144 | 83 | 168 | 168 | 120 | 72 | 46 | | | 89 | 110 | 110 | 44 |
| Hyacinth abundance (L1) | 142 | 536 | 141 | 935 | | 407 | 186 | | | | | 550 | 363 | 284 |
| Plastic densities (L1) | 105 | 388 | 108 | 391 | | 376 | 95 | | | | | 435 | 192 | 274 |

### 2.2 Floating plastic transport

Plastic transport were estimated using the visual counting method, developed by (González-Fernández & Hanke, 2017) and now widely used in observational studies on macroplastic transport (González-Fernández et al., 2021; van Calcar & van Emmerik, 2019). All floating macroplastic and macrolitter items (>0.5 cm) floating at the river surface were counted during a determined time frame at each observation segment. Several observation segments were determined per measurement location, to account for the spatial variability in plastic transport across the river width (van Emmerik et al., 2018). The number of segments depends on the river width of the measurement location. Nine observation segments were selected at L1 (upstream site, river width of 200 m) and twelve at L2 (downstream site, river width of 300 m), enabling to cover respectively 68% and 60%. At each observation segment, two types of observation were conducted: counting of *entrapped* macroplastic and macrolitter, i.e.: items entrapped in hyacinth patches and counting of *free-floating* macroplastic and macrolitter, i.e.: items freely floating at the water surface.

The mean plastic transport observation $F$ [items/hour] for observation point $i$ was calculated using the following equation:

$$F_i = \frac{N_{t,i}}{t_{t,i}} + \frac{N_{f,i}}{t_{f,i}} \tag{1}$$

Here, $N_t$ is the plastic count of items [items] *trapped* in hyacinths and $N_f$ plastic count of *free-floating* items [items] for observation point $i$ during observation $t_t$ and $t_f$ [min], respectively. This distinction between trapped items and free-floating items enables to calculate the ratio of total trapped items over the total count of items, which is reported as a percentage [%]. The total floating plastic transport $F_{total}$ [items/hour] was calculated using the following equation, derived from van Emmerik, de Lange, et al. (2022):

$$F_{total} = \sum_{i=1}^{n} \frac{F_i}{w_i} \cdot W \tag{2}$$

Here, $w_i$ is the observation segment width [m], $W$ the total river width [m]. The observation track width $w_i$ [m] was estimated at 15 m for both measurement locations. We extrapolated floating plastic transport at an annual scale, considering both the mean and median $F_{total}$ for all measurements done over the monitored period, thus calculating both the mean and median annual item transport [million items/year]. We also expressed floating plastic transport in terms of mass transport [tons/year], using the following equation (Vriend et al., 2020):

$$M = F_{total} \cdot \overline{m} \tag{3}$$

Here, $\overline{m}$ expresses either the mean or the median mass per plastic item. We used both mean and median mass because other studies found that plastic transport estimates vary greatly depending on mass statistics (van Emmerik, de Lange, et al., 2022). We used the mass statistics from van Emmerik et al. (2019), who collected and weighted 3,022 items over 45 measurement days at the Saigon river. The mean mass was approximately 10 grams and the median mass 4.3 grams.

### 2.3 Hyacinth abundance

Hyacinth patches were detected using UAV imagery analysis. We used a color filtering approach which enables to separate floating vegetation content from other elements present at the river surface (e.g. water, banks, boats, wooden debris, floating items). This approach leverages the color characteristics of active vegetation in the visible range to distinguish it from other materials. A total of 3,562 UAV images was collected throughout the measurement period. To characterize hyacinth abundance, 3,544 images were ultimately processed. A few images (n = 18) were discarded because these were blurry, taken with a side-angle or due to the presence of boats which interfered with the hyacinth detection. Image processing was done using the Open CV 4.5.4.60 library in Python 3.9.7. In addition to the color filtering, we performed morphological operations over the images, involving noise reduction and dilation to close small gaps. These operations and related parameters are detailed in Supplementary Material (Extended Method). A minimum threshold area (>=0.1 $m^2$) was also defined to filter out individual leaves and branches. All these operation parameters were defined by trial and error through visual inspection, which was performed through a subset of the total UAV image dataset. Trial and error sought to maximize detection and minimize false positives as well as accurately detect the edges of the hyacinth patches. Physical sampling of the patches to estimate plastic densities was not deemed feasible for long-term monitoring, given that the patches typically move within minutes. More details on the processing steps performed and their validation can be found in the Supporting Information (Extended Method). Fig.2 provides an example of hyacinth detection for one UAV image.

We quantify hyacinth abundance in terms of coverage and count of patches. Hyacinth coverage [$km^2/km^2$] was calculated as the total area covered by hyacinth over the total river area considered. The count of patches [#] is expressed as the number of total patches found per measurement unit. For both variables, four measurement units/scales were retained: image, flight, day and month. We include statistics on the mean size of hyacinth patches [$m^2$] in section 2.3.

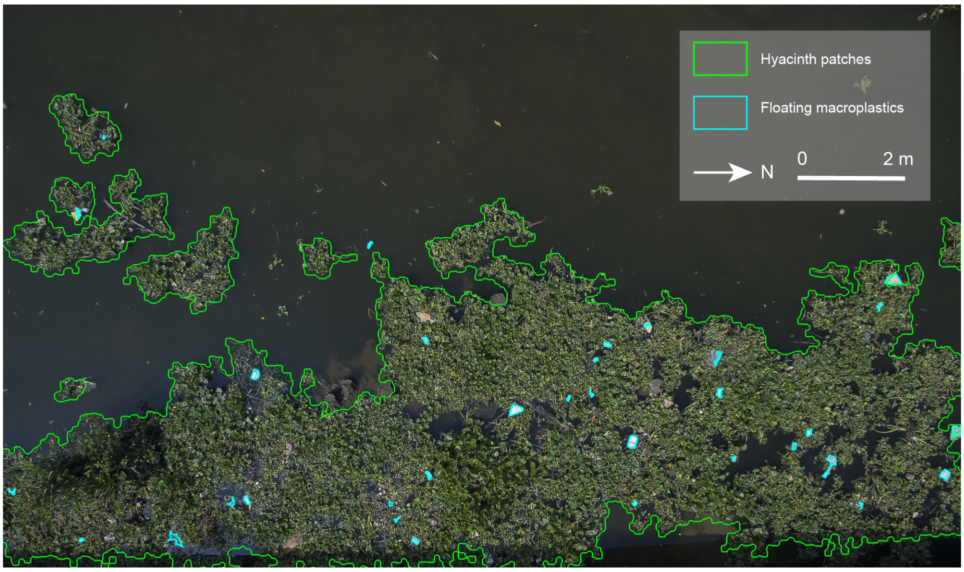


Figure 2: Example of processed UAV image [from 2 February 2021] with floating macroplastics and hyacinth patches identified.

### 2.4 Plastic densities

Plastic densities at the river surface and within hyacinth patches were also quantified using UAV imagery analysis. The approach chosen is similar to the one described for hyacinth detection in the previous section. The detection of floating plastic relied also on a color filtering operation, which filtered pixels of white and light grey color. This approach does not enable to detect all floating macroplastic and macrolitter items, which can be of varying colors, and opacity and transparency levels. However, our visual assessment on the entire dataset led to the conclusion that the majority ($\sim$ 70-90%) of macroplastic and macrolitter items were of this color range. This is consistent with previous studies that quantified macrolitter composition in the Saigon river and demonstrated the high proportion of items such as expanded polystyrene (food packaging, insulation foam), polystyrene (plastic cups and cutlery) and soft polyolefins (plastic bags and foils) (Schreyers, van Emmerik, Luan Nguyen, Castrop, et al., 2021; van Emmerik et al., 2019). Because of this limitation, our estimates of plastic densities should be considered conservative. In addition to the color filtering, morphological operations were also applied to the UAV imagery dataset, i.e. noise reduction with Gaussian filtering and closing of gaps. Overall, processing steps for plastic detection were less computer-intensive than for hyacinth patch detection, mainly due to the smaller size of the objects of interest and the broader homogeneity of items compared to hyacinth patches (edges were more easily distinguished for these anthropogenic items than for the rather loose patches). Additional details on the processing operations and their parameters can be found in the Supplementary Material (Extended Method). An example of plastic detection for one UAV image can be seen on Fig. 1.

Plastic detection could only be implemented after manually removing (by cropping) the area affected by sun glint from each image. Sun glint pixels have the same color characteristics as the detected plastics. Cropping was therefore necessary to avoid false positive detection. Given that many images had a very large glint area, many were completely discarded for plastic detection (n = 1,202). More information on these aspects can be found in the Supporting Information (Extended Methods).

We calculated two types of plastic densities: river surface plastic density, expressing the number of items over the total river area considered and hyacinth plastic density [items/km$^2$], expressing the number of items over the total hyacinth area considered. Plastic densities were expressed both as items densities [items/km$^2$] and mass densities [kg/km$^2$]. For mass densities, we used both the mean and median mass values per plastic item derived from van Emmerik et al. (2019), as described in section 2.2.

### 2.5 Additional data

To better understand plastic and hyacinth abundance in the Saigon river in relation to hydrological processes and their seasonality, we used available data on rainfall and freshwater discharge at the Saigon river. Rainfall and freshwater discharge are measured daily and the resulting datasets are openly and freely available on the website of the Ho Chi Minh City Irrigation Service Management company (http://www.dichvuthuyloi.com.vn/vn/tin-tuc/thong-tin-ve-tinh-hinh-dien-bien-khi-tuong-thuy-van-719/). We extracted all available daily data on rainfall and freshwater discharge at the Saigon river for the year 2021, corresponding to the measurement period for plastic transport, hyacinth abundance and plastic densities. We used the rainfall data measured at the station Mac Dinh Chi, located in the first district of Ho Chi Minh City (latitude: 10.784223242113756; longitude: 106.69904438238632), as this is the closest rainfall measurement station from our measurement sites. River discharge is not measured within Ho Chi Minh City. River discharge is measured in the Tây Ninh province, in the upstream area of the Saigon river and measurements correspond to the Dau Tieng reservoir inflow into the Saigon river. Monthly cumulative rainfall [mm] and mean freshwater discharge [m$^3$/s] were calculated based on the above-mentioned rainfall and discharge data and are presented in Fig. S2.

### 2.6 Statistical analysis

The variables presented in the previous sections were aggregated at various temporal scales to identify temporal trends. We aggregated values by seasons, with the dry season spanning from December to May and the wet season from June to November, as rainfall and water flow seasonality are key components of the hydrological regime of the Saigon river (Camenen et al., 2021). To test whether the mean ranks of hyacinth coverage, plastic densities and plastic transport are significantly different between dry and wet seasons we used the Kruskal-Wallis test, which does not assume a normal distribution of the data. For the daily and monthly aggregation levels we tested the Spearman correlations between pairs of variables. The spatial distribution of plastic densities, plastic transport and hyacinth coverage across the river was also investigated. The averaged cross-sectional spatial distribution was calculated based on daily means for the metrics considered. We tested the similarity in spatial distribution also using Spearman correlations. We characterized different regimes (see Results and Discussion, section 3.2) of plastic transport and hyacinth coverage. For this, we used the median values to distinguish between high and low categories of transport and coverage values.

## 3 Results and Discussion

### 3.1 Plastic density in hyacinths ten times higher than at river surface

On average, between 55% and 65% of floating macroplastic is being transported by hyacinth patches, depending on the location and the flow direction considered (L1, landward: 65%, seaward: 55%; L2, landward: 56%, seaward: 57%). We found that hyacinths cover an average of 6% of the river surface, therefore indicating that patches trap much more floating debris than could be hypothesized solely based on their relative coverage of the river surface. This is confirmed by the discrepancies observed between river surface and hyacinth plastic densities, with the latter being approximately one order of magnitude higher than the former (mean river surface plastic density: $2.5 \cdot 10^4$ items/km$^2$ and mean hyacinth plastic density: $2.1 \cdot 10^5$ items/km$^2$) (Table 3). These results confirm that hyacinths act as physical traps for floating plastics. Plastic transport in fluvial systems affected by hyacinth invasion are therefore not only influenced by the two-way interactions between water and particles, but are also likely affected by the movement of hyacinth at the water surface and changes in patch coverage. These include the growth and reduction of individual patches, as well as the aggregation and separation of patches among themselves.

Plastic item transport was estimated on average between 109 and 372 million items/year, for L1 and L2 respectively (Table 3), approximately two orders of magnitude higher than the top plastic polluted rivers in Europe (González-Fernández et al., 2021). Mean and median plastic mass transport estimates vary by a factor of approximately two (Table 3), depending on whether a mean or median mass per item was considered. This highlights the uncertainties associated with estimating plastic mass transport values. In addition, our estimates focus on the total plastic transport (i.e. the total volume of plastic being transported in the river, irrespective of the flow direction). Given that the Saigon river is strongly affected by tidal dynamics, a distinction between total and net plastic transport (i.e. the total volume of outgoing plastic) should be made in further studies and will be further discussed in section 4 (Synthesis and Outlook).

Mean item plastic densities at the river surface are 36 times higher ($2.5 \cdot 10^4$ items/km$^2$) than those found in the Great Pacific Garbage Patch (GPGP) ($6.9 \cdot 10^2$items/km$^2$) (Lebreton et al., 2018). The average plastic mass densities found at the river surface (102-250 kg/km$^2$ for mean and median mass densities, respectively) are 3 to 6 times higher those observed in the GPGP (mean mass density: 42 kg/km$^2$), a likely result of the heavier items found in the ocean compared to river plastic. The highest plastic density found in our observations ($4.7 \cdot 10^5$ items/km$^2$) is 190 times higher than the top density for the GPCP ($2.4 \cdot 10^3$ items/km$^2$) (Lebreton et al., 2018) and was measured for plastic trapped within hyacinths. Overall, this comparison between river and ocean plastic densities supports the hypothesis that most plastics is retained in rivers and not emitted into the oceans (van Emmerik, Mellink, et al., 2022). We also show that within rivers, aquatic floating vegetation such as hyacinths act as physical traps of floating plastics, accumulating even higher densities of plastics than otherwise found at the river surface.

Table 3: Floating transport and plastic densities estimates. We here report absolute values for floating plastic transport, irrespective of the flow direction.

**Floating transport**

| | Item transport [items/year] | | Mass transport: Mean mass/item [tonnes/year] | | Mass transport: Median mass/item [tonnes/year] | |
|---|---|---|---|---|---|---|
| Location(s) | Median | Mean | Median | Mean | Median | Mean |
| L1 | 90 | 109 | 903 | 1098 | 386 | 469 |
| L2 | 243 | 372 | 2447 | 3740 | 1045 | 1598 |

**River surface plastic density**

| | Item density [items/km$^2$] | | Mass density: Mean mass density [kg/km$^2$] | | Mass density: Median mass density [kg/km$^2$] | |
|---|---|---|---|---|---|---|
| Location(s) | Median | Mean | Median | Mean | Median | Mean |
| L1 | $2.4 \cdot 10^4$ | $2.5 \cdot 10^4$ | 239 | 250 | 102 | 107 |

**Hyacinth plastic density**

| | Item density [items/km$^2$] | | Mass density: Mean mass density [kg/km$^2$] | | Mass density: Median mass density [kg/km$^2$] | |
|---|---|---|---|---|---|---|
| Location(s) | Median | Mean | Median | Mean | Median | Mean |
| L1 | $1.8 \cdot 10^5$ | $2.1 \cdot 10^5$ | 1830 | 2107 | 782 | 900 |

### 3.2 Temporal variability in hyacinth abundance and plastic accumulation and transport

All variables related to hyacinth abundance, plastic densities and transport have a clear seasonality, with higher hyacinth and plastic loads during the dry season (Dec-May), compared to the wet season (Jun-Nov) (Fig. 3). Only for the river surface plastic density no significant statistical difference was found between dry and wet seasons (p-value=0.14); however, the mean river surface plastic density was 1.3 times higher during the dry season compared to the wet season (mean river surface plastic density for the dry and wet seasons, respectively: $2.8 \cdot 10^4$ items/km$^2$ and $2.1 \cdot 10^4$ items/km$^2$). Plastic transport variables (Fig. 3 E-H) have stronger significant values compared to metrics related to hyacinth abundance and plastic densities, especially for the site L2 (downstream location). This study monitored hyacinth coverage at one location over the river (L1, upstream location), but results are consistent with other studies that considered a larger geographic area. Janssens et al. (2022) characterized hyacinth abundance over a larger portion (115 km of river length and 12,64 km$^2$) of the Saigon river and showed that the dry season corresponds to higher water hyacinth abundance. Hyacinth coverage is the variable with the strongest correlation with plastic transport (Spearman $\rho$=0.86, p-value<0.05 for both L1 and L2) at a monthly scale (Table 4). Plastic densities were not found to be significantly correlated with plastic transport at a monthly scale. However, the Spearman correlation coefficients were found to be quite high and p-values close to significance level (all p-values<=0.2 and $\rho$>=0.46), suggesting that such a relation might exist but is not highlighted with the current data at a monthly scale, probably due to the relatively short time-series. Plastic densities were found to be significantly correlated with the number of hyacinth patches (Spearman $\rho$=0.82, p-value<0.05 and Spearman $\rho$=0.68, p-value<0.1 for hyacinth and river surface plastic density, respectively) but not with hyacinth coverage at a monthly scale (p-value>0.1). This highlights that high hyacinth plastic density values typically coincide with a high number of patches, but not necessarily with large hyacinth coverage.

The monthly time-series provide a more detailed view of the seasonal cycle in hyacinth coverage, plastic loads and transport throughout the year (Fig.4). The peak in plastic transport occurs between March and May (Fig.4 A-B): March for the seaward transport at the downstream site, May at the upstream site and April for landward transport at both locations. The highest plastic densities at the river surface and within hyacinths

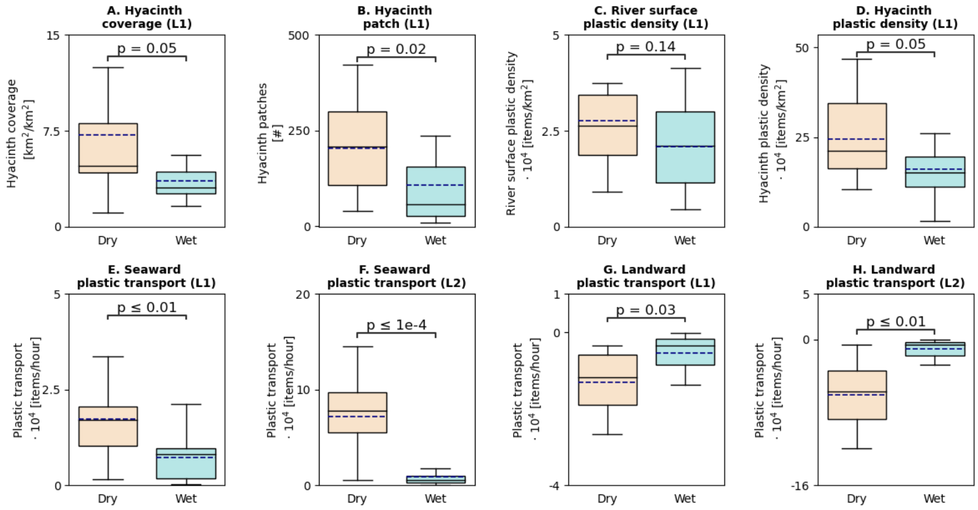


Figure 3: Seasonality at the Saigon river for A. Hyacinth coverage (L1) B. Hyacinth patch (L2). River surface plastic density (L1) D. Hyacinth plastic density (L1) E. Seaward plastic transport L2 F. Seaward plastic transport (L2). G. Landward plastic transport (L1). H. Landward plastic transport (L1). The blue dotted line indicates median values. Statistical differences between the dry (Dec-May) and wet (Jun-Nov) seasons were tested using the Krustal-Wallis test. p-values are indicated on top of each pair of boxplots. Values are considered statistically significant for p-value<=0.05.

Table 4: Spearman correlation coefficients between hyacinth abundance, plastic densities and transport variables. Variables were aggregated at both monthly and daily scales. Values marked with * indicate p-value<0.1, **< 0.05,***< 0.01. The absence of sign indicates p>0.1

| | Hyacinth coverage [km$^2$/km$^2$] (L1) | | Hyacinth patch [#] (L1) | |
|---|---|---|---|---|
| | Monthly | Daily | Monthly | Daily |
| River surface plastic density [items/km$^2$] (L1) | 0.64 | 0.36* | 0.68* | 0.02 |
| Hyacinth plastic density [items/km$^2$] (L1) | 0.32 | -0.29 | 0.82** | 0.41** |
| Plastic transport [items/hours] (L1) | 0.86** | 0.11 | 0.64 | 0.47** |
| Plastic transport [items/hour] (L2) | 0.86** | 0.08 | 0.43 | 0.38* |

| | River surface plastic density [items/km$^2$] (L1) | | Hyacinth plastic density [items/km$^2$] (L1) | |
|---|---|---|---|---|
| | Monthly | Daily | Monthly | Daily |
| Hyacinth coverage [km$^2$/km$^2$] (L1) | 0.64 | 0.36* | 0.32 | -0.29 |
| Hyacinth patch [#] (L1) | 0.68* | 0.02 | 0.82** | 0.41** |
| Plastic transport [items/hours] (L1) | 0.46 | 0.08 | 0.57 | 0.54*** |
| Plastic transport [items/hour] (L2) | 0.61 | -0.04 | 0.54 | 0.29 |

are registered during the month of February. This also corresponds to the month with the highest number of patches. Hyacinth coverage, on the other hand, is at its highest in March. It should be noted however, that variables for plastic densities and hyacinth abundance were not monitored during the month of April. Janssens et al. (2022) estimated hyacinth coverage over three years at the Saigon river, using satellite imagery. The time-series analysis showed that peaks in hyacinth typically occur between the end of February until the end of April. May and June mark the decline in all the variables studied. These months correspond to the start of the wet season over the Saigon river. For the year 2021, an increase in discharge and rainfall was observed starting from April and intensified from June onward (Supporting Information, Fig. S2). Few data were available between June and October, thus limiting our understanding of the full cycle of plastic loads over the wet season and the start of the post-monsoon season (Nov-Dec). van Emmerik et al. (2019)) observed a peak in plastic transport in September and October, based on observations conducted in 2018. Such a peak was not observed in the present study, despite the absence of data in August and September. The following months (Oct-Dec) generally correspond to an increase in all studied variables compared to the previous months (Jun-Sep). Overall, the monthly variations in plastic transport, densities and hyacinth coverage show similar trends but are not strictly synchronous. The noted discrepancies could result from gaps in data collection. However, they could also indicate a temporal lag between the different processes of plastic accumulation and transport.

At at a daily scale, hyacinth coverage and plastic transport are not significantly correlated for both upstream and downstream locations (p-value>0.01) (Table 4). No significant correlations were found between river surface plastic density and plastic transport for daily values either. Positive and statistically significant correlations were however found for other variable combinations. Hyacinth plastic density (L1: Spearman $\rho$=0.54, p¡0.01) and hyacinth patch quantities (L1: Spearman $\rho$=0.47, p-value<0.05, L2: Spearman $\rho$=0.38, p-value<0.01) have significant and positive relations with plastic transport for one or both monitored locations at a daily scale. One reason for the absence of correlation at daily scale between hyacinth coverage and plastic transport might be related to a temporal lag in the processes of hyacinth abundance and plastic transport. Fig.5 A and B detail the time-series of plastic transport, hyacinth coverage and river surface plastic density at L1 for two periods (March and May-June 2021). Both time-series clearly show first a peak in plastic transport, followed a few days later by an increase in hyacinth abundance and plastic densities (hyacinth coverage and river surface plastic density). In March, the peak in hyacinth coverage and plastic densities is asynchronous, with hyacinth coverage increasing 5 days before the highest river plastic density is observed. This is not the case for the period of May-June, where the peaks are registered on the same day. A likely explanation for this time lag between the transport and accumulation processes pertains to the succession of mobilization and retention processes. We hypothesize that high river discharge first mobilizes floating materials (including plastic and hyacinths), which get transported within the river system. Then, reduced water flows (probably due to tidal dynamics and/or seasonality in the net discharge) can cause a decrease in observed plastic transport for the same considered location. Simultaneously, low flow velocities cause the accumulation of plastic and hyacinths in certain parts of the river channel, for instance on its lateral sections. At L2 (downstream location), additional plastic inputs from the HCMC canals could also contribute to increased plastic densities in low flow conditions. Plastic densities and hyacinth abundance increase on the lateral sections of the river; until an increase again in discharge flushes the deposited debris again.

Overall, plastic transport, plastic densities and hyacinth abundance are closely linked. With few exceptions, all the variables studied show a correlation with plastic transport either at a daily or monthly scale. For certain variables (e.g.: hyacinth coverage and river surface plastic density), the temporal lag observed in transport and accumulation processes demonstrates that plastic transport is best predicted when considering a wider time-frame than the daily scale. Satellite images are not available at a daily resolution with sufficiently high spatial resolution to detect hyacinths in rivers. Hyacinth coverage can be estimated with freely available satellite imagery every 5 to 7 days (Janssens et al., 2022) for the same location. This allows to build reliable monthly hyacinth coverage estimates, making it a suitable proxy for plastic transport and accumulation in the Saigon river. The current observations indicate that monthly means in hyacinth coverage can be a good predictor of plastic transport.

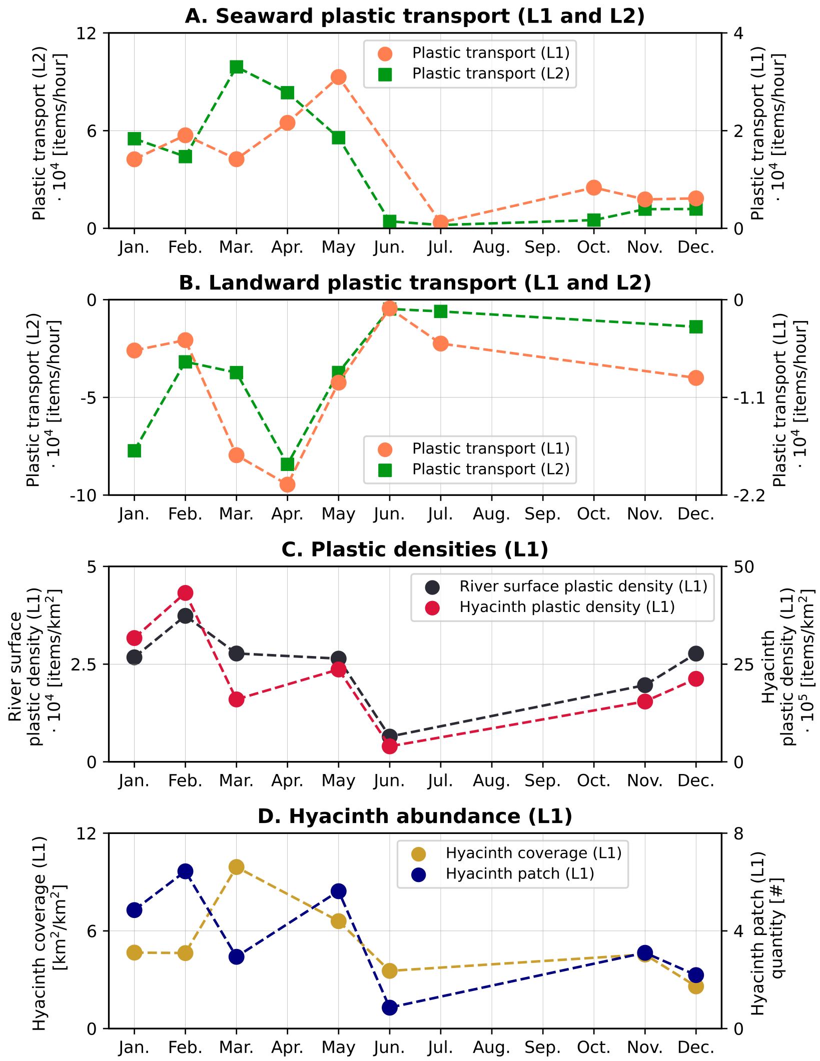


Figure 4: Monthly averages of variables related to plastic transport (A-B), plastic densities (C) and hyacinth abundance (D)

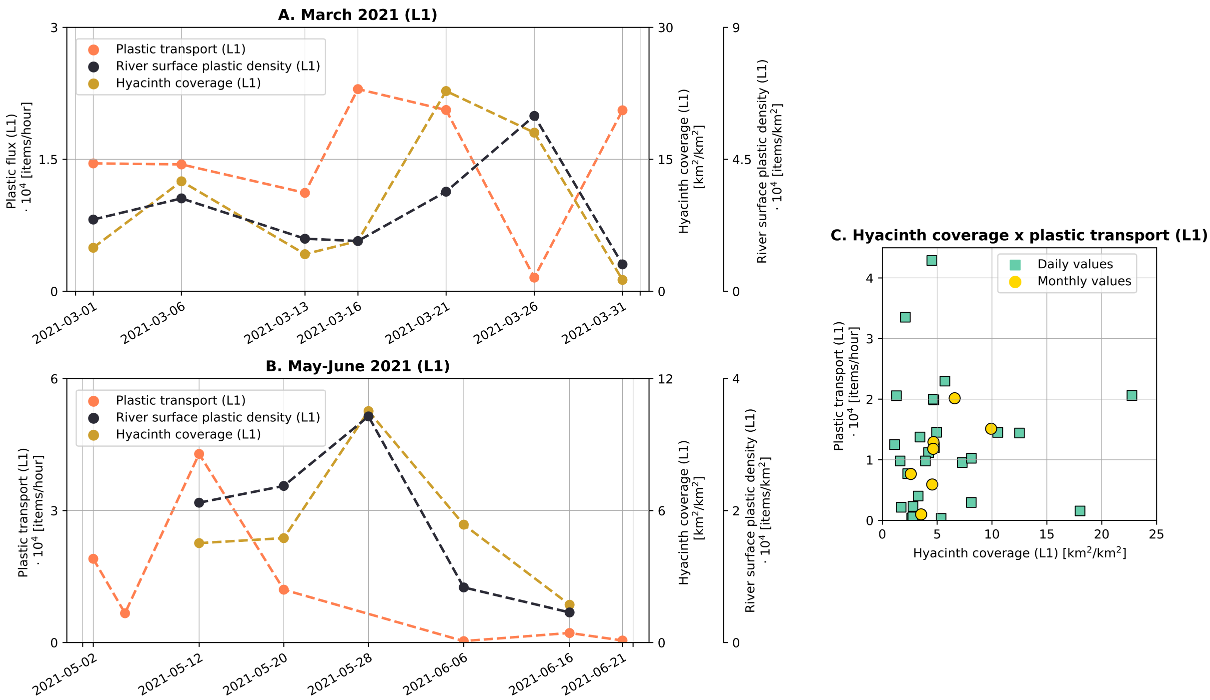


Figure 5: Observed daily values in hyacinth coverage, plastic transport and river surface plastic density at L1. A. Detailed time-series for the month of March 2021. B. Detailed time-series for the period of May-June 2021. C. Hyacinth coverage versus plastic transport at L1, daily and monthly mean values (Spearman $\rho$ = 0.11 and 0.86, respectively, p-values>0.1 and <0.05).

### 3.3 Spatial variability in hyacinth abundance, plastic densities and plastic transport

Plastic transport are approximately 3 to 4 times higher at L2 (downstream) than at L1 (upstream). On average, the seaward transport is estimated at 4.4 $\cdot 10^4$ items/hour for L2 and 1.4 $\cdot 10^4$ items/hour for L1. The average landward plastic transport is -4.9 $\cdot 10^4$ items/hour for L2 and -1.0 $\cdot 10^4$ items/hour for L1. This difference in plastic transport between locations could be explained by additional quantities of plastic inputted between the monitored locations, a likely factor given that the river passes through Ho Chi Minh City's urban area. In addition, stronger tidal influence at L2 compared to L1 probably limits net discharge and net plastic transport, thus increasing plastic transport found in the water regardless of additional plastic inputs between monitored locations. Our current data did not quantify tidal dynamics and its effects on plastic transport, but lower net plastic transport can be expected at L1 given its more upstream position in the river.

Plastic densities were not monitored during this study at L2, but we compared our results for L1 with data from a previous study that reported such values for the same month (May). Similarly to this study, Schreyers, van Emmerik, Luan Nguyen, Phung, et al. (2021) used UAV imagery to estimate river surface plastic density, hyacinth plastic density and hyacinth patch size. These estimates were done only for the month of May 2020 at L2, which we compare with the L1 values found for May 2021. At L2, hyacinth plastic density was estimated at 2.1 $\cdot 10^6$ items/km$^2$. In this study, we found a value of one order of magnitude lower at L1 (2.4 $\cdot 10^5$ items/km$^2$, average for May 2021) than L2. River surface plastic density was also found to be higher at L2 (5.0 $\cdot 10^5$ items/km$^2$) compared

Table 5: Plastic transport, densities and hyacinth coverage at L1 and L2. (1) indicates values from Schreyers, van Emmerik, Luan Nguyen, Phung, et al. (2021). (2) indicates values from Janssens et al. (2022). In the latter, hyacinth coverage was monitored along several large reaches of the Saigon river using satellite imagery. Two of the monitored section include L1 and L2. Plastic densities and average hyacinth patch size are reported for the month of May 2021 for this study and May 2020 to allow comparison across studies. Hyacinth coverage values are here reported as the average over a 3-year time-series.

| | Seaward plastic transport [items/hour] | Landward plastic transport [items/hour] |
|---|---|---|
| L1 | $1.4 \cdot 10^4$ | $-1.0 \cdot 10^4$ |
| L2 | $5.0 \cdot 10^4$ | $-4.5 \cdot 10^4$ |
| | **River surface plastic density [items/km$^2$]** | **Hyacinth plastic density [items/km$^2$]** |
| L1 | $2.5 \cdot 10^4$ | $2.2 \cdot 10^5$ |
| L2 | $5 \cdot 10^5$ (1) | $2.1 \cdot 10^6$ (1) |
| | **Average patch size [m$^2$]** | **Hyacinth coverage [km$^2$/km$^2$]** |
| L1 | 1.5 | $1.4 \cdot 10^1$ (2) |
| L2 | 0.82 (1) | $9.5 \cdot 10^{-2}$ (2) |

to L1 ($2.6 \cdot 10^4$ items/km$^2$). The higher plastic densities found at L2 confirm that larger riverine plastic quantities are present downstream. The increase in hyacinth plastic densities downstream can also be partially explained by a decrease in hyacinth coverage between L1 and L2. Janssens et al. (2022) estimated hyacinth coverage continuously for three years (2018-2020) over a large portion of the Saigon river, including the two locations of this study. Between 2018 and 2020, on average, the midstream section (where L1 is situated) had approximately 15 times larger hyacinth coverage than the downstream area (where L2 is located). In addition to a decrease in hyacinth coverage, hyacinth patches are also of a smaller size downstream than upstream. Schreyers, van Emmerik, Luan Nguyen, Phung, et al. (2021) estimated hyacinth patch average size at L2 at 0.82 m$^2$ in May 2020. In this study, we found that hyacinth patches were on average twice as large in size at L1 (size of 1.5 m$^2$, average for May 2021). This decrease in hyacinth patch size is likely the result of mechanical break-down due to boat traffic and possibly higher flow velocities (Petrell & Bagnall, 1991). This comparison across studies bears many uncertainties, mainly because it assumes that the temporal variation in hyacinth and plastic densities is negligible between May 2020 and May 2021. Given the high temporal variability in plastic densities observed in this study, and the intrannual variability in hyacinth coverage found in Janssens et al. (2022), such an assumption is probably incorrect. For instance, between 2018-2020, hyacinth coverage was found to vary by as much as a factor of eight for the month of May (Janssens et al., 2022). This factor however, remains much lower than the difference found in hyacinth coverage between L1 and L2 (of a factor of 15). We can therefore reasonably infer that hyacinth coverage decrease and plastic transport and densities increase along the river course still holds. Upstream of Ho Chi Minh City, hyacinth can cover a large extent of the river surface, up to 24% of the river surface (Janssens et al., 2022). As the hyacinth drift downstream of the city, patches get destabilized and break-down into smaller patches. Overall, the hyacinth coverage decreases, covering on average less than 0.1% in its most downstream section. Conversely, the plastic densities at the river surface and within hyacinth are higher downstream than upstream of Ho Chi Minh City. The higher quantities in plastic result in higher plastic transport downstream than upstream of the city.

In addition to spatial variation between upstream and downstream locations, the horizontal spatial variability (i.e.: across the river width) is also an important factor to understand the nexus between hyacinth abundance and plastic accumulation and transport processes. Overall, we did not find that plastic densities, plastic transport and hyacinth abundance all followed a similar horizontal spatial distribution (Fig. 6 A-B). Our findings show that high transport of plastics can coincide with both high hyacinth coverage, which occurs in the lateral reaches of the river; or with low hyacinth coverage in the middle of channel. Our observations suggest that the drivers for these two high transport modes are of different nature. The first is mainly driven by the mobilization of hyacinth patches, the second is more closely tightened to variations in flow velocities and plastic quantities found in the river.

Hyacinths tend to accumulate on the sides of the river channel, where the flow velocity is lower. Both the coverage and number of patches gradually decrease towards the middle of the river channel (Fig. 6A). River surface plastic density follows a similar distribution (Fig. 6B) and was found to be positively correlated with hyacinth abundance (hyacinth coverage:$\rho$=0.84, p-value$<$0.01, hyacinth patch: $\rho$=0.47, p-value$<$0.05). A peak in river surface plastic density was however observed at 80 m from the West bank, in a section of the river with low hyacinth coverage ($<$4% on average). Hyacinth plastic density and plastic transport, on the other hand, have a more complex and chaotic spatial distribution, with a succession of peaks and drops in values (Fig. 6B). An overall trend is difficult to establish. No strong significant correlation was found between these variables and hyacinth abundance, or among themselves (all $\rho<0.2$). For plastic transport, two main areas where high plastic transport typically occur can be distinguished. One is at around 25 m from the West riverbank, in an area with generally high hyacinth coverage and high plastic densities. Plastic transport is also relatively high at approximately 120 m from the West riverbank, in an section with low hyacinth coverage. The discrepancies in the spatial distribution of plastic densities is explained by the fact that one considers the river area as its reference, and the other the hyacinth coverage. High hyacinth plastic densities can be observed in areas with low surface plastic densities and hyacinth abundance, notably in the case of high quantities of plastic present in small hyacinth patches. Overall, we can distinguish four modes of transport and accumulation across the river (Fig. 6C). On both lateral sides of the river channel high coverage of hyacinth dominates. This high accumulation is combined with both low and high transport rates. Both hyacinth and plastic tend to accumulate in this area, due to low current velocities. When the current increases, hyacinths get mobilized in batches and important quantities of plastic and hyacinth are then washed out, resulting in high plastic transport. On the lateral reaches of the river, plastic transport is therefore intermittent, alternating periods of low plastic transport and high accumulation (deposition dominated) with 'washed-out' periods (transport dominated). One main unknown is the thresholds in flow conditions (stream velocity and water level) necessary to destabilize these temporary deposition zones. In the middle reach of the river channel, both high and low plastic transport rates can be found as well, hyacinth coverage is generally low. Hyacinth patches do not cover large portion of the river surface there, are highly mobile and generally present in small amount.

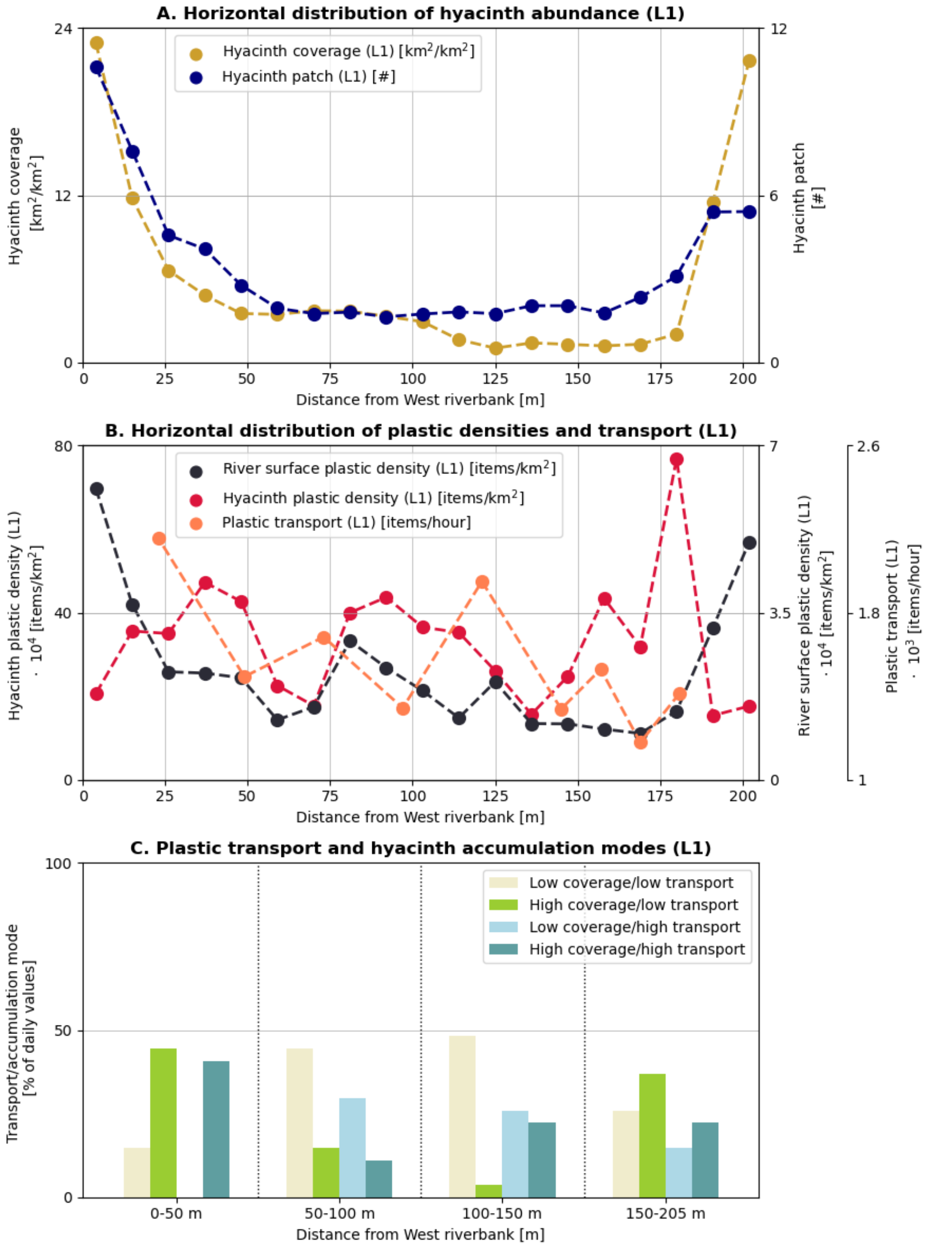


Figure 6: Horizontal distribution of hyacinth abundance (A) and plastic densities and transport (B) Plastic transport / hyacinth accumulation modes (C). Daily values were averaged across the river section.

# 4 Synthesis and Outlook

## 4.1 Summary

In this study, we demonstrated the role that hyacinths have in accumulating and transporting floating plastic. We found that $\sim 60\%$ of transported items are trapped within hyacinth patches, and that hyacinth plastic densities are on average one order of magnitude higher than otherwise found at the river surface. In comparison, the highest plastic densities found in the Great Pacific Garbage Patch are 190 times lower. Hyacinths function as major temporary sinks for floating plastics; however this trapping effect varies greatly both in time and space. Our analysis showed that on a temporal scale, high plastic transport and hyacinth coverage tend to co-occur, especially when considering a monthly to seasonal scale. This is likely the result of a time-lag between plastic transport and hyacinth coverage peak events at a sub-monthly scale. Plastic densities, hyacinth coverage and plastic transport are all higher during the dry season (Dec-May) when compared with the wet season (Jun-Nov) At a spatial scale, we identified different transport modes in relation to hyacinth coverage. Depending on the sections of the river, different mechanisms can explain high plastic transport rates. In the lateral sections of the river, low surface flow velocities and the abundance of high hyacinth coverage promote the temporary deposition of large quantities of items, with limited transport rates (Fig. 7A). Increased surface flow velocities mobilize in batches of these temporary accumulation zones, leading to high plastic transport rates (Fig. 7B). In the middle of the channel, plastic items are less affected in their trajectories by hyacinth-water interactions, and move therefore more freely at the water surface. We hypothesize that the intermittent transport on the lateral reaches of the river is mainly governed by semi-diurnal variations in river flow, caused by tidal dynamics.

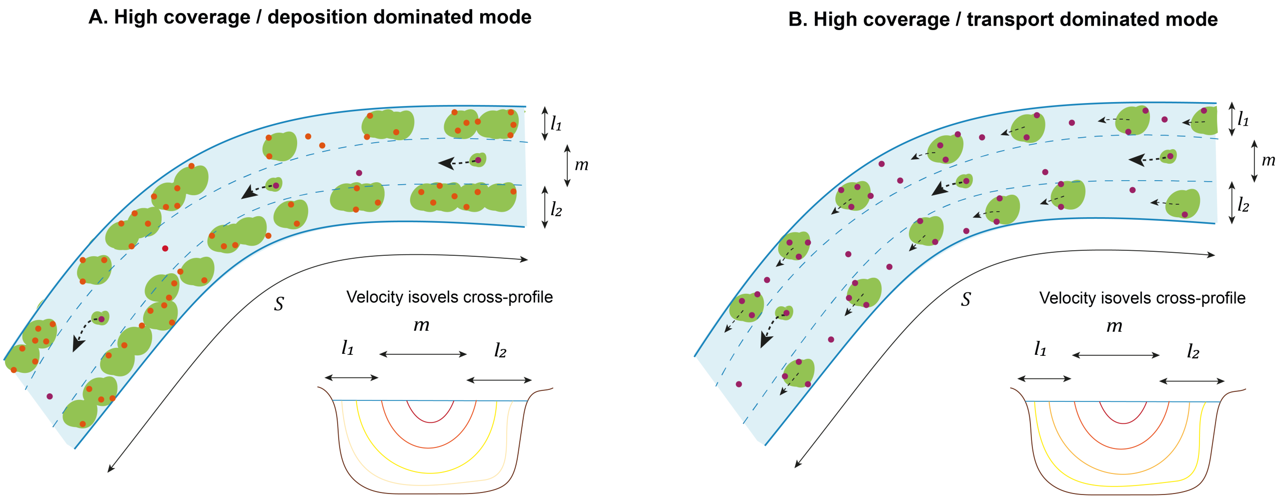


Figure 7: Variation in plastic transport modes on the lateral reaches of the river channel depending on hyacinth coverage. A. Deposition dominated mode, hyacinths and plastic have limited mobility during low flow conditions. B. Transport dominated mode, the hyacinths and plastic are mobilized in batches. $S$ is the total longitudinal section of the river considered, $l_1$ and $l_2$ correspond to the lateral sections of the river, and $m$ signifies the middle section. The cross-sectional views schematize the velocity isovels, with lower flow velocity on the lateral section of the river during a deposition dominated mode.

### 4.2 Conceptual model for plastic-hyacinth interactions

Fluvial plastic transport is affected by several hydro-meteorological and ecological factors (Schreyers, van Emmerik, Luan Nguyen, Castrop, et al., 2021; Hurley et al., 2018; Roebroek et al., 2021; van Emmerik, de Lange, et al., 2022) (Fig. 8A), of which hyacinth coverage is a key component for tropical rivers. Low rainfall rates during the dry season both limit freshwater discharge (Fig. S2) and net plastic transport, but generate an increase in hyacinth coverage (Camenen et al., 2021; Harun et al., 2021; Janssens et al., 2022). This is likely the result of the higher nutrient concentrations found in the water during periods of low net river discharge. In turn, increased hyacinth coverage also alters plastic transport, with high rates of (temporary) deposition within hyacinths. In-stream vegetation (floating and submerged) can function as a resistance force to water flows in certain systems (Wharton et al., 2020; Sand-Jensen, 1998; Cornacchia et al., 2020) and ultimately regulate surface flow velocities and water levels. We hypothesize that because of this influence on the riverine flow dynamics, high hyacinth abundance also affects fluvial plastic transport, by causing a (temporary) trapping of items, thus ultimately decelerating transport transport. During the wet season, the lower coverage of hyacinths results in lower deposition/accumulation rates of plastic items within patches compared to the dry season. The role of hyacinths as aggregators and temporary sinks is therefore more limited during this season. The fate of plastic could be affected by this in two distinct ways. Items could flow more freely at the water surface, probably leading to longer transport trajectories. Another likely scenario is that limited hyacinth coverage facilitates the contact and deposition of plastic in other compartments, such as riparian vegetation or riverbanks. In such a case, the higher hyacinth abundance during the dry season can be considered as a barrier to other accumulation processes. Plastic deposition in these compartments would probably result in longer deposition periods, because they can be considered more stable (e.g. less frequently affected by hydrological dynamics).

The above-mentioned interactions between hyacinth coverage, plastic densities and net discharge affect the seasonality in plastic transport (Fig. 8B). We can distinguish three phases in the annual plastic transport cycle: an accumulation phase, a flushing phase and a baseflow phase. The accumulation phase corresponds to the bulk of the dry season (Dec-Mar). During this phase, the Saigon's net discharge is low, with even negative net discharge monthly values registered for some years (Camenen et al., 2021). Net discharge estimates were not available for the year 2021. However, measured freshwater discharge and rainfall rates in 2021 also suggest low net discharge rates for the period spanning from December to March (Fig. S2). In this accumulation phase, plastic densities are gradually increasing due to the cumulative effect of additional plastic inputs and limited net downstream plastic transport. Most plastics therefore remain into the river, moving upstream and downstream depending on the flow direction. High total plastic transport rates are observed, mainly governed by the high plastic densities found in the river. A large part of the transported items are most likely not flushed out of the system, because of the relative low net discharge.

At the beginning of the wet season (Apr-Jun), the increased net discharge generates a flushing effect (Fig. S2). Most items are transported downstream and plastic densities in the river channel therefore decrease. Higher flow velocities destabilize hyacinths, which tend to break-down more easily. Other studies also observed that increased precipitation rates can be associated with the seasonal reduction in hyacinth coverage during the wet season (Janssens et al., 2022; Harun et al., 2021). During the wettest months (Jul-Nov), rainfall levels, freshwater discharge (Fig. S2) and thus net discharge (Camenen et al., 2021) are at their highest. However, plastic transport rates are low during this period, as a result of a drop in plastic densities during the previous flushing phase (baseflow phase).

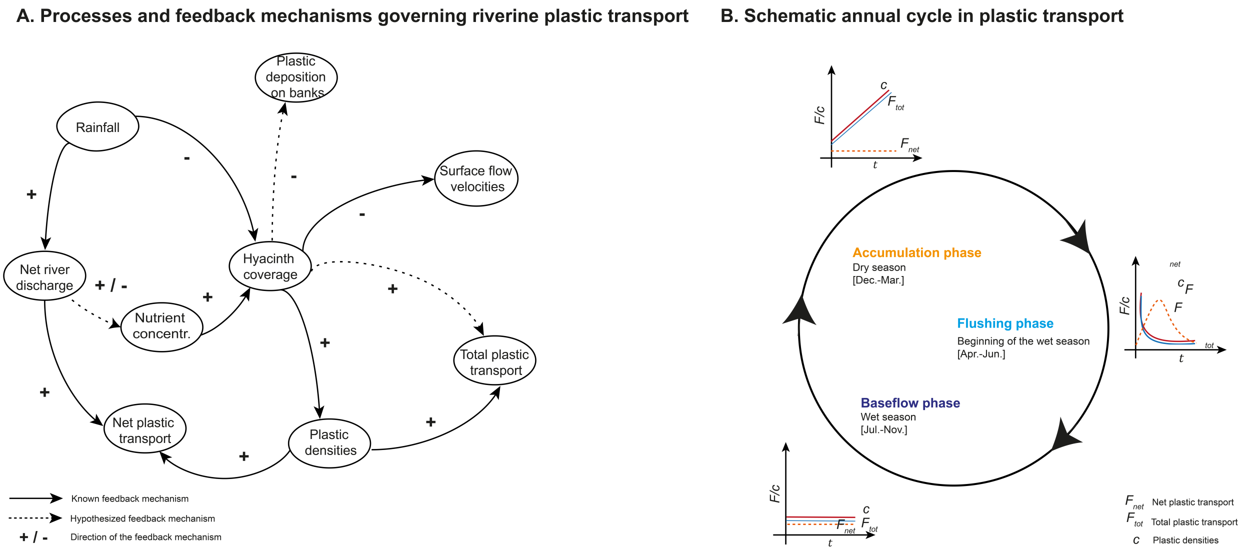


Figure 8: Overview of plastic transport processes in the Saigon river, under the assumption of constant plastic influx. A. Processes and feedback mechanisms governing riverine plastic transport B. Schematic annual cycle in plastic transport.

### 4.3 Discontinuity in plastic transport

This study confirmed that hyacinths alter fluvial plastic transport by generating discontinuous effects at various levels. The majority of plastics are trapped by hyacinths (∼60%), despite hyacinth only covering ∼6% of the river surface, thus confirming the role of hyacinths as major accumulators of plastics (*physical discontinuity*). The fate of plastic transport in rivers is therefore impacted not only by water-particle interactions but also by the interactions with floating vegetation. As a result, the presence of hyacinths generates different transport modes, with different accumulation and release dynamics between areas where hyacinth are abundant and less affected areas. For instance, an intermittent transport mode was observed on the lateral sections of the river (*spatial discontinuity*). In addition, the seasonality in net river discharge similarly affects both hyacinth coverage and plastic transport. In the accumulation phase, high hyacinth coverage alters the temporary deposition and release dynamics of plastics, because items are more often and more likely temporarily deposited and released by hyacinths. Without such large hyacinth coverage, the deposition mechanisms of plastic would likely be dominated by interactions with the banks, with seasonal release timescale, whereas transport mechanisms would be entirely governed by daily flow dynamics (*temporal discontinuity*).

### 4.4 Outlook

For tropical river systems heavily affected by tidal influence and seasonal variation in river net discharge, such as the Saigon river, distinguishing between net and total plastic transport is essential. Estimating the net plastic transport is however challenging, as it requires to take into account: a) ebb and flood phases during the semi-diurnal tidal cycles; b) neap and spring tides, and c) annual net discharge cycle. The net transport of items over a river longitudinal section can be expressed as the product of seaward and landward plastic transport within a predetermined area. Factors affecting the variation between seaward and landward transport include tidal dynamics, variations in freshwater discharge and the resulting seasonality in net water discharge, as well as deposition mechanisms in other river compartments.

Current observation techniques and protocols are limited in time and space, and do not enable accurate quantification of net plastic transport in rivers. The timescales of observations are inappropriate to estimate plastic mobility, especially in systems with fluctuating transport regimes such as tidal rivers, and systems heavily affected by temporary deposition mechanisms (for instance due to high floating vegetation presence). For our observations, both landward and seaward plastic transport were considered, but monitoring was not carried throughout entire tidal cycles and thus we could not accurately quantify net plastic transport. Continuous measurements throughout tidal cycles are needed to further characterize plastic mobility in rivers. Techniques such as tracking of the mobility of individual particles, for instance with GPS trackers (Ledieu et al., 2022; Newbound, 2021; Tramoy et al., 2020) and continuous transport measurements over tidal cycles could help in better understanding plastic transport mechanisms.

Despite characterizing hyacinths as temporary sinks of plastics, we could not quantify deposition times of plastics within hyacinths, nor do we know the hydraulic conditions at which accumulations of hyacinth-plastic are entrained. This aspect is particularly important as it likely determines the alternation between mobile and relatively stable phases of hyacinths-plastic mobility and ultimately affects the timescale of fluvial plastic transport. Furthermore, to better understand the overall role of hyacinths as temporary sinks of plastics and how this relates to other components of the river system, studies on transport and temporary deposition mechanisms across various riverine compartments are needed. Extending direct observations is one way forward, but presents certain challenges. First, it is usually time consuming and can sometimes be costly. Second, isolating the explaining variables is often challenged by the inherent complexity and heterogeneity of the observed systems. Another way forward could involve testing hypothesis on deposition and transport dynamics of plastic within vegetation and other sinks through controlled laboratory experiments. This could be done for instance by building physical models that test under which hydraulic conditions floating plastics are mobilized and deposited in various river compartments. Nevertheless, extending field-based research to other tropical systems is a necessary step to further explore the role of hyacinth in trapping and transport plastics.

## 5 Conclusions

Hyacinth function as a major temporary sink for riverine floating plastics. Plastic densities in hyacinths were found to be 10 times higher than at the river surface and $\sim$ 60% of the total transported items were trapped by hyacinth patches. These plant-plastic dynamics are not unique to the main observation location, as similar findings were also found for another location in the Saigon river. This suggests that the results are transferable to other sites within the river, as well as to other fluvial systems invaded by hyacinths.

Temporally, peaks in plastic transport and hyacinth coverage coincide, especially on a monthly to seasonal scale. A time-lag in peak events was observed at a sub-monthly scale. These findings suggests that to a certain extent, hyacinth coverage could be used as a proxy for plastic pollution. In addition, we showed that hyacinths are a key component in explaining plastic transport mechanisms. Peaks in plastic transport are caused either by high transport governed by daily flow dynamics - mainly in the middle of the channel -, or by high accumulation of hyacinth-plastics in the lateral sections of the river, which can be mobilized in batches.

We linked hyacinth coverage and plastic accumulation to hydrological factors in a conceptual model, which can be used to explain spatio-temporal variations in plastic transport. A crucial aspect is the distinction between net and total river discharge, which likely drives changes in net/total plastic transport and hyacinth coverage at the river scale. We identified three phases (accumulation, flushing, baseflow phases) throughout the year which explain the annual variation in net and total plastic transport within the river.

Overall, hyacinth abundance in tropical rivers alters floating plastic transport because it interferes with the two-way interaction between water and plastic items. Because they trap the majority of plastic items, the mechanisms driving hyacinth movement and temporary deposition at the river surface also influence plastic propagation in rivers. As major temporary (and mobile) sinks of plastics, hyacinth abundance lead to increased discontinuity in plastic transport.

## 6 Data availability

All the UAV images used in this study are publicly available at https://doi.org/10.4121/21648152.v1. All remaining data will be made publicly available upon publication and have been included in the submission documents.

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# Supporting Information for "Discontinuity in fluvial plastic transport increased by floating vegetation"

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## Supporting Information 1: Extended method

### UAV surveys

We used the DJI Phantom 3 UAV, with comes with a FC6310 camera, equipped with a 1/2.3 inch CMOS sensor. The sensor has a maximum resolution of 12.76 megapixels and a camera resolution of 2992 x 3992 pixels. The UAV operated automatically, from take-off to landing. The programming was done with the Drone Harmony app. All images were captured at nadir, i.e. perpendicular (90°± 0.02°) to the direction of the flight, to facilitate surface calculations. Each flight lasted approximately ten minutes. The UAV imagery analysis involved coverage detection of hyacinths. The pixel area had to be converted to real-ground area, by calculating the ground sampling distance ($d_g$)

[m/pixels], as follows:

$$d_g = \frac{S_w \cdot H_f}{F_l \cdot w_i} \quad (1)$$

Here, $S_w$ is the sensor width of the camera [m], $H_f$ is the flight height [m], $F_l$ is the focal length of the camera [m] and $w_i$ is the image width [pixels]. All variables as the camera used did not change and the flight height was set at 10 m. A $d_g$ value of $3.8 \cdot 10^{-3}$ m/pixel was found.

**Hyacinth and plastic detection with UAV imagery analysis**

In this section, we detail the processing steps taken for both hyacinth and plastic detection (Fig. S1). The choice in the RGB threshold values was done by trial and errors over a subset of the imagery dataset. For the hyacinth detection, the same threshold values were applied for all the analyzed images. For the detection of plastic, changes in brightness between images did not allow to use the same threshold values for the entire dataset. A few combinations were therefore retained and tested over batches of images (corresponding usually to the same measurement day). The best fitting threshold values were retained for the batch of images analyzed. For hyacinth detection, images were then blurred with a Gaussian filter, to reduce noise. Noise in hyacinth detection is the result of the configuration of patches. In general, patches were relatively loose (with gaps and holes in-between) with highly irregular edges. Various filter sizes were tested (see Sensitivity analysis in the Validation subsection). Ultimately, a filter size of 13 × 13 pixels was retained for the hyacinth detection. No Gaussian blurring was necessary for the detection of plastic items, as the target objects are of relatively small size and the detection approach sought to maximize edge detection from the background elements rather than reduce noise. For hyacinth detection, a dilate operation was necessary to reduce unnecessary details at the edges of patches. A final kernel size of 17 × 17 pixels was selected after trial and errors through visual inspection. A fill in (e.g.: binary closing) operation was performed for both detection approaches. This allows to fill in small gaps within the detected objects of interest. The closing is applied around a circle of a specified diameter [in pixels]. A diameter of 10 pixels was chosen for both hyacinth and plastic detection.

### Sun glint and false positives with plastic detection

No recurring distinct shapes of sun glints that could be of use to automatically filter these areas out were recognized throughout the entire UAV imagery dataset. We do not deemed feasible therefore to implement an automatic detection of sun glint and opted for manual removal of sun glint affected area, using a simple cropping operation. The cropping was done by batch of images. In images taken during the same UAV flight and same overpass direction, the area covered by sun glint was generally located in the same region of the images.

### Validation

#### Sensitivity analysis for hyacinth detection

We explored the sensitivity of the output variables for hyacinth abundance [hyacinth coverage and count of patches] to variations in input parameters for the three morphological operations performed (Gaussian blur, dilate and fill-in operations). The sensitivity analysis was performed over a representative subset of the imagery dataset (n = 156 images, 4% of the total number of images analyzed). We performed a Mood's median test to compare the median of the two datasets. The alpha risk value was set at 0.05. We found a p-value $> 0.05$ (p-value=0.11), indicating that the null hypothesis is confirmed and no significant difference can be assumed between the two sample populations.

For each morphological parameter, we calculated the change in output values for the count of patches and mean and median coverage area [%], based on changes in input parameters [%]. Changes in input parameters were computed for approximately -50, -30, -10, 10, 30 and 50%. Given that kernel sizes have to be odd numbers, small deviations from the above-mentioned changes in input were sometimes necessary to fulfill this requirement. Ultimately, we expressed the sensitivity in terms of slope factor [%], calculated as the ratio between the change of output and the change of input parameters:

$$s = \frac{c_o}{c_i} \tag{2}$$

Here, $c_o$ is the change in output parameter and $c_i$ in input parameter. The sensitivity analysis results (Table S1) show that the dilate parameter is the most sensitive, with a higher dilate kernel leading to a lower number of patches and higher hyacinth coverage.

### Assessment of plastic detection

We assessed the accuracy of our detection approach of floating plastic items by manually labelling items on a subset of our dataset (n = 273, 10% of the image dataset used for plastic detection). This validation set of images was selected randomly, using the sample function in Python. We again performed a Mood's median test to compare the median of the two datasets and test the whether the validation set can be considered representative of the entire imagery dataset. We found a p-value $> 0.05$ (p-value=0.22), indicating that the null hypothesis is confirmed and no significant difference can be assumed between the two sample populations.

We manually identified and counted all floating items, irrespective of their size, on the validation set. An accuracy ratio [%] $a_r$ was computed for each image, as follows:

$$a_r = 100\% - \frac{|c_d - c_m|}{c_m} \cdot 100\% \tag{3}$$

Here, $c_d$ is the total number of floating items detected with the detection approach on a given image and $c_m$ the total number of floating items manually labelled. The overall accuracy ratio [%] was computed as the mean of accuracy ratios per image. We found an overall accuracy ratio of 75%. The number of floating items was found to be exactly the same between the validation and our detection approaches for 52% of the images (n = 141). For 37% of the images (n = 102), the detection approach underestimated the number of floating items when compared with the manual labelling. Only for a minority of the images (11%, n = 31) the detection approach overestimated the number of floating plastic items.

## Supporting Information 2: Rainfall and freshwater discharge at the Saigon river

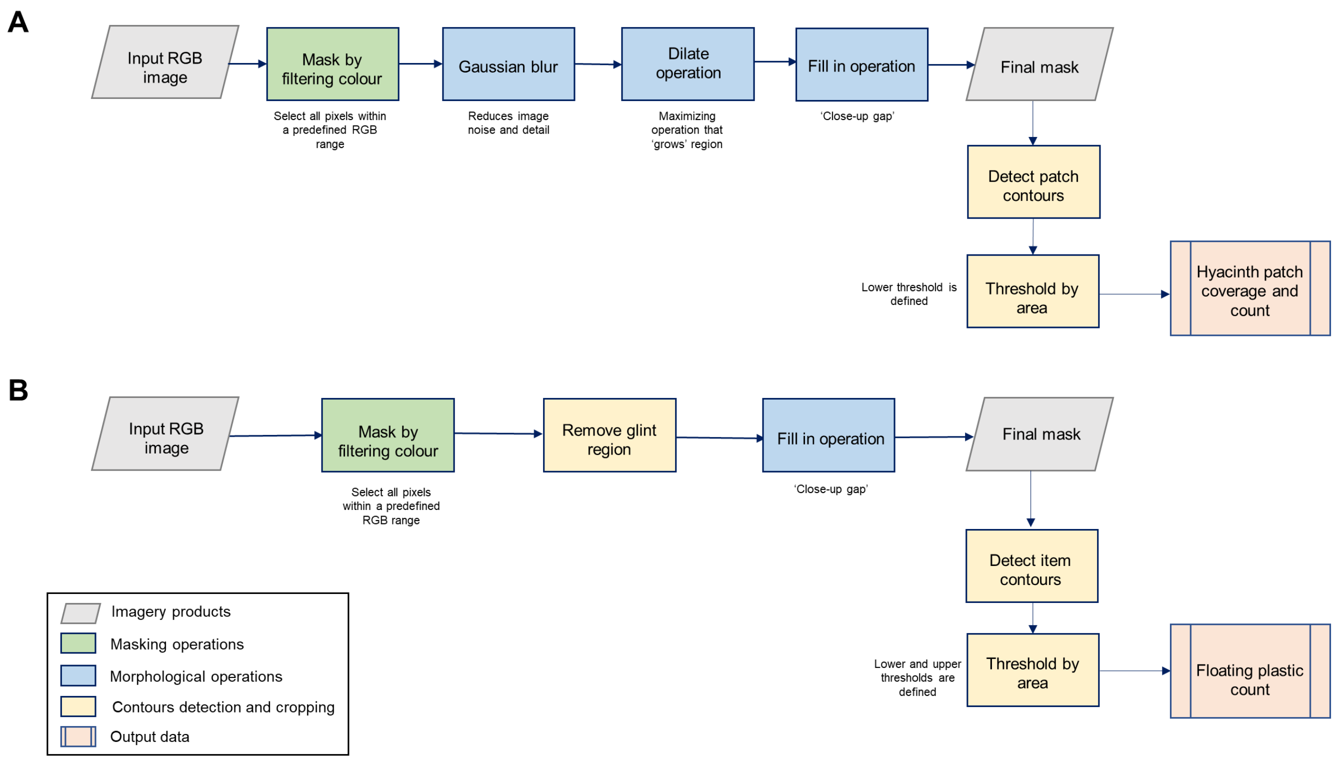


Figure S1: Processing steps to detect: A. Hyacinth patches and B. Floating plastic items.

Table S1: Sensitivity analysis for input parameters (morphological operations) in hyacinth detection on UAV images. This table reports the slope factor $s$, expressed in %.

| | Dilate | Gaussian | Closing |
|---|---|---|---|
| Hyacinth patch | -54 | -21 | -5 |
| Mean hyacinth coverage | 55 | 25 | 4 |
| Median hyacinth coverage | 64 | 28 | 12 |

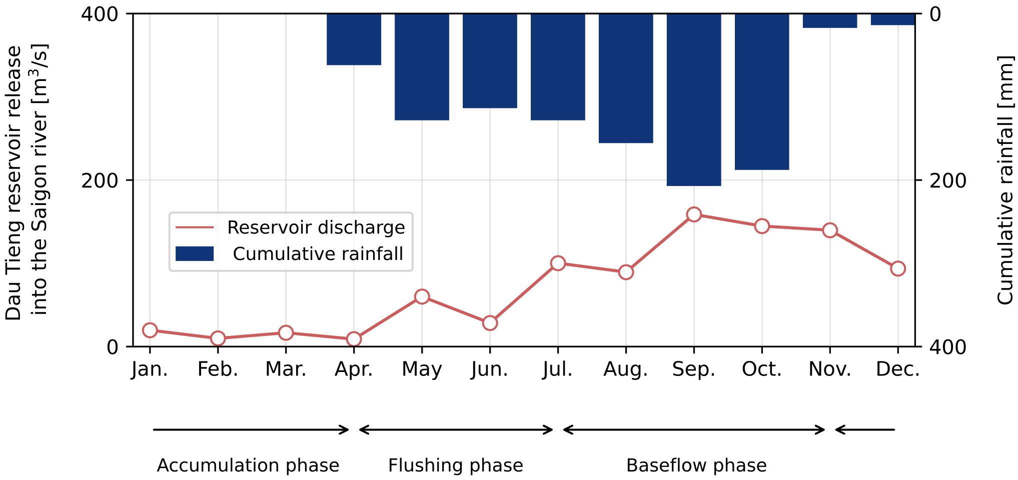


Figure S2: Monthly rainfall and freshwater discharge at the Saigon river, for the year 2021. The rainfall data was monitored at the Mc ĩnh Chi station in District 1, Ho Chi Minh City. The freshwater discharge (mean values) from the Dau Tieng reservoir into the Saigon river was measured at the Tây Ninh station. The three phases indicated refer to plastic transport/hyacinth coverage phases, as conceptualized in section 4.2.