Faculty of Civil Engineering and Geosciences

Multidisciplinary Project - Group 345
CEGM3000

Characterization of plastic transport in the Saigon River

An analysis of the river stretch that crosses Ho Chi Minh City conducted in the rainy season

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1 Abstract

The Saigon River, coursing through Ho Chi Minh City, is a vital yet alarmingly polluted waterway. It ranks among the top 50 rivers globally contributing to plastic pollution, as highlighted by Lebreton et al. (2017). This study delves into the complex mechanisms governing the transport of floating plastic within a tidal system, such as the Saigon River.

Our methodology adopts a multifaceted approach, combining visual observations, on-site measurements, and a comparison with existing literature data and methodologies. The factors influencing plastic transport in the studied river stretch are several and complex, ranging from the seasonal fluctuations in rainfall and tidal patterns to the role played by water hyacinths, acting as effective catchments for plastic litter, thus shaping the trajectory of these materials. Furthermore, we investigate the different types of plastic that flow on the river surface.

At the end of our research, we develop an early-stage conceptual model. This model serves as a framework that could help understanding plastic transport within the Saigon River and emphasizing the interplay of numerous influencing factors.

Our findings underscore the necessity for comprehensive investigations into plastic transport in the Saigon River. By addressing these knowledge gaps, we can develop more effective strategies to mitigate plastic pollution.

2 Preface

This report is the final deliverable of the Master Course CEGM3000 Multidisciplinary Project at the Delft University of Technology. This project offers the opportunity for students to apply their engineering and scientific skills in a real context. Coming from different backgrounds, we had the opportunity to work in a multidisciplinary team and put together our knowledge of Hydraulic Engineering, Resource and Waste Engineering and Climate and Weather Science.

We spent 10 weeks in Ho Chi Minh City, Vietnam from September 1, 2023 to November 10, 2023. We had the opportunity to get in touch with realities and contexts that we had never encountered before in our life. Living in such a different environment was a challenging and extremely enriching experience that shaped our personalities and made us grow under different points of views.

Our research was supported by TU Delft and two Vietnamese local researchers, Mr. Bui Le Than Khiet and Dr. Vo Thi Kim Khuyen. No local university or company was involved in this research, with the exception of the two researchers mentioned above. Our outcomes could be used for future studies to obtain a more extensive understanding on the analysed problem. The primary aim of this project was to gain knowledge on the issue of plastic pollution of rivers. Specifically, we focused on the Saigon River, studying the stretch of the river which flows through Ho Chi Minh City. The time spent in Vietnam was organised such that the entire month of September was mainly dedicated to field measurements and literature review for the support of our study. The remaining weeks were dedicated to data analysis and the development of this report.

Many people supported us in this research. First and foremost, we would like to express our sincere gratitude to Dr. Riccardo Taormina for the financial support that he provided and for his continuous assistance throughout our research, including its planning phase. We also wish to thank our track supervisors for their availability and guidance during the development of this project: Dr. Wim Uijttewaal, Dr. Marc Schleiss and Dr. Maarten Bakker. Additionally, our appreciation goes to the TU Delft Global Initiative and FAST Fund for their financial contributions that made this project possible. Another acknowledgment goes to The Ocean Cleanup for the willingness they demonstrated in assisting us. Lastly, we would like to extend our gratitude to Mr. Bui Le Than Khiet and Dr. Vo Thi Kim Khuyen for their on-site support and their extensive knowledge of the Saigon River and the study area, which proved to be indispensable for the success of this project. Finally, we would like to thank all the researchers that previously conducted studies in the same area through which we gathered essential understanding of the problem.

Figure 1:
Pictures from our experience in Vietnam.

3 Introduction

To comprehensively tackle the escalating issue of plastic pollution and its impact on river ecosystems, it is crucial to understand the intricate dynamics that underlie this problem. High levels of plastic pollution within rivers cause a range of issues, including reduced availability of potable freshwater, damage to urban infrastructure, and a threat to local flora and fauna (van Emmerik and Schwarz (2019)). The consequences are palpable and underscore the urgency of addressing this pressing concern.

Rivers are also the primary contributors to plastic input into the seas (Meijer et al. (2021)), with a total estimated plastic input of about 500 kilotons per year (Kaandorp et al. (2023)). Vietnam is among the top 10 nations responsible for massive plastic release into surface water bodies (Lebreton et al. (2017)).
Vietnamese rivers exhibit a far higher accumulation of plastic items compared to major European rivers. In particular, the Saigon River is among the top 50 rivers that globally contribute the most in plastic pollution of water bodies (Lebreton et al. (2017)).

Our study aimed at gaining a better understanding on the problem of macroplastic pollution of the Saigon River. Specifically, we focused on flowing litter transport in the stretch of the river that flows through Ho Chi Minh City. To do so, we analysed different variables and factors that are believed to play a role in transport dynamics. We believe that it is of extremely importance to understand the dynamics of pollutants such as plastic items in a highly contaminated system like the Saigon River. Comprehending these dynamics could be a starting point to organise cleaning campaigns and ideally set the river free from part of the huge amount of plastics that pollute it.

The project mainly focused on the stretch of the Saigon River limited by Phu Long Bridge upstream and Thu Thiem Bridge downstream. The study area is highly influenced by tidal forcing, being characterized by a semi-diurnal tidal regime with two ebb and two flood tides alternating everyday. As a results, plastic fluxes flow both seaward and landward directed. Moreover, Ho Chi Minh City is located in the southern part of Vietnam, characterized by the annual alternation of a dry and a rainy season. Our study mainly focused on the analysis of plastic transport dynamics observed in the month of September, which belongs to the rainy season. Nevertheless, we also conducted comparisons with data from other time periods, allowing for a comprehensive understanding of the plastic pollution phenomenon.
Several studies have been conducted to estimate global riverine emissions of plastic into the sea. However, only a few studies consider the crucial role of tidal dynamics. In the Saigon River, tides increase the retention time of floating plastic litter and prevent the huge amount of floating plastic to be released into the sea (Lotcheris et al. (2023)).

Plastic fluxes, together with hydrological parameters such as free surface flow velocities and river depths have been measured multiple times at different locations and during different tidal phases in the whole month of September, as described in section 6. These measurements have been used to obtain values of cross-sectional plastic fluxes and river discharge daily, coupled with rainfall data obtained through hourly precipitation maps provided by Global Precipitation Mission (GPM). Furthermore, estimates of the same parameters from previous studies have also been used to allow comparison and determine the existence of seasonality patterns in these parameters.

In section 7, the key findings of our research are presented. Firstly, an analysis on rainfall data and plastic flux estimates is performed for both our measurements and available literature. By doing so, it is possible to highlight whether rainfall has an influence on plastic fluxes and hydraulic parameters such as river discharge and water level. Secondly, an analysis on hydraulic parameters of the Saigon River and their influence on plastic transport is conducted. At first, the effect of tides is addressed, then plastic fluxes are coupled with discharge values to define a dependency relation between the two. In these section we also show the cross sectional distribution of floating plastic litter in the Saigon River, as highlighted by our observation campaigns. A paragraph addressing plastic concentrations and the formation of accumulation zones follows, highlighting the crucial role of these areas in the reduction of plastic fluxes downstream of the study area and closer to the sea.
Another important factor that plays a role in floating plastic transport dynamics in the Saigon River is the presence of invasive riverine plants such as the water hyacinths. This plants covers a significant area of the study stretch and cause important problems to the river, both from an ecological and an anthropogenic point of view. Section 7.5 shows the results of our study regarding the role of riverine vegetation in plastic litter capture.

In the end, an analysis of the variation of plastic transport rates through the river stretch is presented, followed by a categorisation of the most relevant plastic litters that flows in the river.
We further introduce a conceptual model that integrates the impacts of all the analyzed parameters on plastic transport. This model could serve as a starting point for future validation and refinement, aiming to precisely quantify the influence of each variable.
In conclusion, our study provides a brief overview of potential remediation methods for cleaning the Saigon River in Ho Chi Minh City, which could be carried out by single citizen groups to contribute to the Saigon River's cleanup.

4 Study Area

The area in which we have conducted our research is a part of the Saigon River, specifically the stretch that flows through Ho Chi Minh City from the upstream boundary of Phu Long bridge to the downstream reach of Thu Thiem bridge, as highlighted in Figure 2.

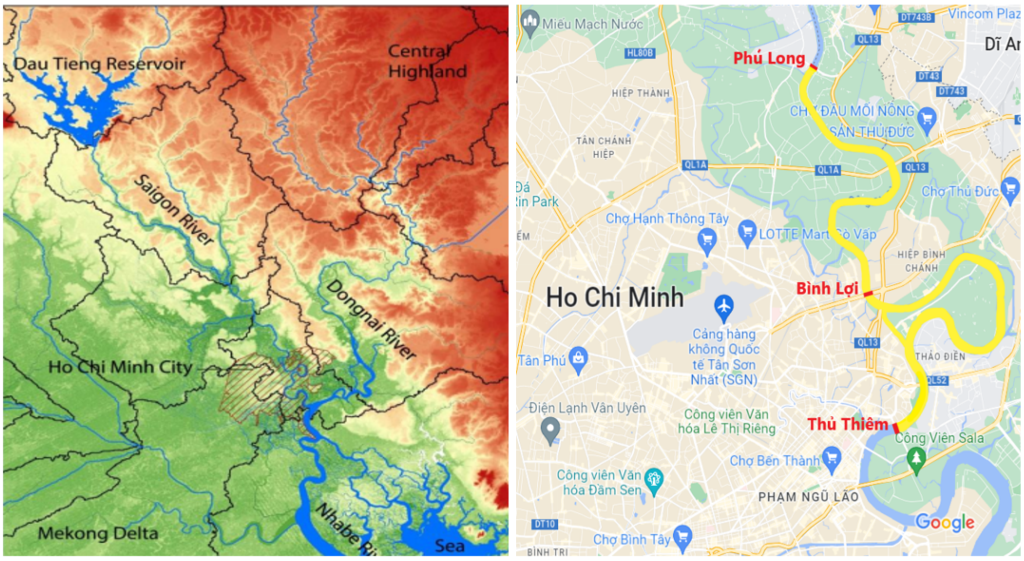


Figure 2:
The Saigon River system (Nguyen (2013)) and the study area. We studied the stretch of river between Phu Long Bridge and Thu Thiem Bridge.

The Saigon river originates in Cambodia and flows into the Dau Tieng reservoir, approximately 120 km north of Ho Chi Minh City (Nguyen et al. (2020)). Before entering the city, the river crosses agricultural areas of paddy rice and rubber plantation. The river shows a high sinuosity with several meanders, which become more regularly shaped and larger when entering Ho Chi Minh City. The study area is in a low elevated zone, between 0 and 10 m above mean sea level (Lotcheris et al. (2023)).

South of the Vietnamese megalopolis, the river flows downstream forming a confluence with the Dong Nai River. There, the Dong-Nai Saigon River system branches into several channels that meander in the Can Gio mangrove forest before entering the East Sea (Dijksma et al. (2010)). From the downstream reach of the selected control volume to its mouth, the river flows for approximately 60 km. The considered stretch of the Saigon River is highly influenced by tides. In particular, the Saigon River is subject to a semi-diurnal tidal regime with a tidal range varying from -2 to 1.50 m, usually resulting in two ebb tides and two flood tides daily (Camenen et al. (2021)).

Tidal estuaries form the interface between rivers and coasts and they are the proxy through which plastic emission in the seas occurs. In tidal rivers, net water flow is the result of the interaction of river discharge and coastal processes such as tides. The resulting flow, which can be quantified with the net discharge (Section 6.4), can be directed either seaward or landward. Seaward directed flow in tidal systems is called ebb flow or ebb tide, while landward directed flow is known as flood flow or flood tide. The period over which the water flow direction switches is called slack water or slack tide. During slack tide, flow velocities are very low, in the order of 0 m/s.

The discharge of the Saigon river varies seasonally roughly between a few tens of m^3/s and 1500 m^3/s in both ebb and flood directions. Discharge values of the Saigon River are the result of complex interaction between tidal mechanisms, rainfall contribution and the controlled water volume periodically released from the Dau Tieng Reservoir. With the storage capacity of $1.58 \cdot 10^9$ m^3, the reservoir was built in 1985 for flood protection, irrigation purposes and for the control of saline water intrusion. Specifically, during the dry season, the discharge is highly influenced by the amount of freshwater released from the reservoir (Nguyen et al. (2019)). The mean annual discharge is 50 m^3/s (Nguyen et al. (2021) , Camenen et al. (2021)).
The region of South Vietnam, in which the Saigon River is located, is characterized by a tropical monsoon

climate. The average humidity ranges between 78 % and 82 % annually, while the annual mean temperature is 28.5 (±1.0) °C (Nguyen et al. (2019)).

In Southern Vietnam, the year is divided into two distinct seasons: the wet and the dry season. The wet season extends from May to October, while the dry season goes from December to April.
With an average rainfall of 1800 $mm/year$, the wet season gathers about 80 % of the yearly precipitation in Ho Chi Minh City (Camenen et al. (2021)). During this season, rain events are more frequent and can be very severe. Precipitation records can locally exceed 300 mm/day (Camenen et al. (2021)). During the dry season the climate is dry and hot. In fact, this season only accounts for approximately 15 % of the total annual precipitation.

5 Context

The increase of plastic pollution is a worldwide pressing issue: plastic production is projected to reach 34 billion metric tons by the year 2050 (Bellasi et al. (2020)). This topic presents a significant environmental concern with far-reaching implications, including the alarming ecological crisis resulting from the infiltration of plastic waste into rivers. This phenomenon has evolved into a global crisis and has given rise to the formation of waste patches in oceans worldwide. The proliferation of plastic pollution in surface waters, seas, and oceans now poses an exceptional challenge to the well-being of our planet (Filho et al. (2022)).

The propensity of plastics to enter and persist within marine ecosystems is strongly influenced by factors such as their durability, low recycling rates, versatile range of applications and inadequate waste management practices. The release of plastics into the marine environment occurs through various pathways, including transportation via rivers and the atmosphere, littering on beaches, and direct introduction at sea through aquaculture, shipping, and fishing activities. Furthermore, in tidal tropical systems such as the Saigon river, the amount of plastic entering the ocean is influenced by the massive presence of floating vegetation, that contributes in entrapping plastic floating items and tend to accumulate close to the banks of the river, where they may ultimately deposit (Lotcheris et al. (2023)).
Riverine plastic pollution not only has adverse effects on the environment and human health but also contributes to ocean pollution. Several factors contribute to riverine plastic pollution, with the main ones including improper waste management practices, the unsustainable habit of discarding plastic into rivers and waterways, urban proximity to water bodies, the presence of dams and litter traps, the influence of seasonal rainfall patterns, variations in river discharge rates, and the unpredictable occurrence of floods (Van Calcar and Van Emmerik (2019)).

Among the top 10 nations globally responsible for releasing significant quantities of plastics into surface water bodies, notable mentions include Malaysia, Indonesia, Thailand, and Vietnam; the high concentration of plastic inputs from river characteristics of these countries, can be observed in Figure 3. In particular, rivers in Vietnam exhibit an alarming accumulation of plastic items per hour compared to European countries. These disparities can be attributed to a complex interplay of cultural distinctions, economic development levels, educational standards, and the efficacy of environmental regulations. To put this into perspective, the cumulative count of plastic items per hour in six out of eight rivers studied in Southeast Asian nations stands at 7100, contrasting sharply with the combined figure of 250 items per hour observed in rivers in France, Italy, and The Netherlands (Van Calcar and Van Emmerik (2019)).

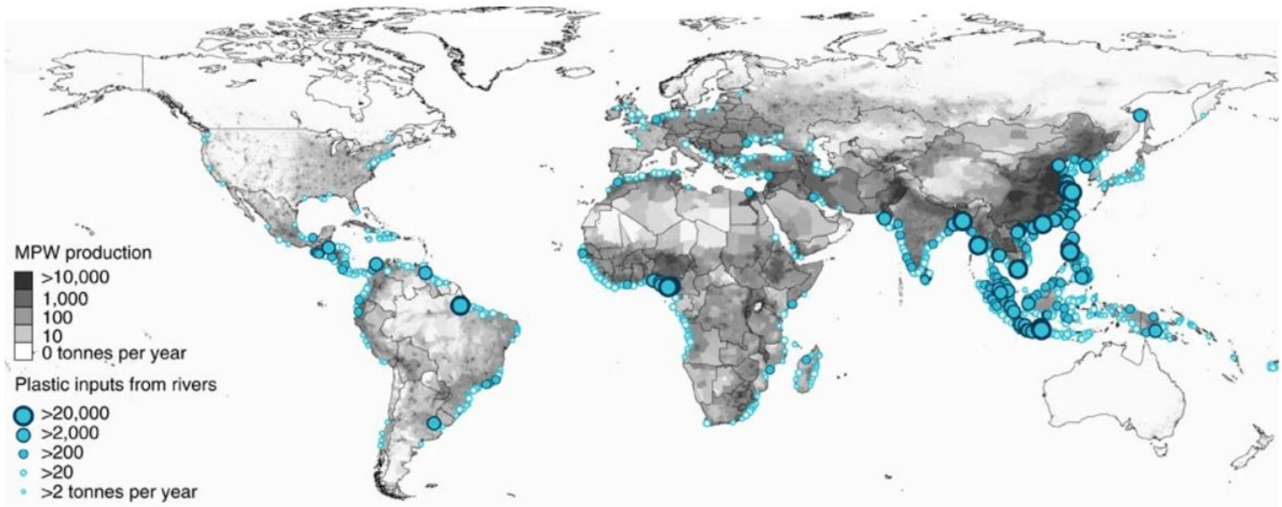


Figure 3:
Mass of river plastic flowing into oceans in tonnes per year (Lebreton et al. (2017)).

The Saigon River in Vietnam holds the fifth position among the largest contributors of plastic pollution in the country and ranks 45th globally, highlighting the severity of the plastic waste issue (Lebreton et al. (2017)). The Saigon River flows through Ho Chi Minh City, Vietnam's economic center, which has an approximate population of more then 9 million residents (Macrotrends (2023)). Ho Chi Minh City, like many other large

cities in Southeast Asia, grapples with a significant challenge in managing its solid waste, in 2016 Ho Chi Minh City was characterised by a daily output of 8.17 tons of solid waste (Verma et al. (2016)) which is now expected to be higher considering that the population of the city increased of almost one million inhabitants from 2016 to 2023 (Macrotrends (2023)).
The escalation in industrialization, urbanization, economic development, and population growth, coupled with improved income levels and enhanced lifestyles, has collectively contributed to a pressing issue in Southeast Asia. This, combined with the absence of proper regulations and policies on solid waste management that characterize Southeast Asian countries, has led to a significant increase in the volume of municipal solid waste and the associated challenges and problems related to solid waste management within the region.

As previously mentioned, Ho Chi Minh City witnessed the daily generation of approximately 8.17 tons of solid waste, with 6.80 to 7.00 tons attributed to municipal solid waste (MSW). This resulted in a daily waste generation rate of 1.02 kilograms per capita (Verma et al. (2016)). In this context, plastic emerged as the third most prevalent component of solid waste in Ho Chi Minh City, comprising 16 % of MSW in terms of dry weight and 25 % of MSW in terms of wet weight. Plastic waste is primarily originated from households, schools, restaurants, and hotels. According to regulations in Ho Chi Minh City, approximately 85 % of municipal solid waste is landfilled, while only the remaining 15 % is recycled, primarily for composting purposes.

5.1 Stakeholders analysis

As previously underlined in the beginning of this Section, the issue of plastic pollution is a pressing concern in Vietnam and mainly in Ho Chi Minh City being the biggest centre of the country. The problem necessitates collaboration among a variety of stakeholders.
This section provides an analysis of the key stakeholders involved in addressing this problem, categorizing them into active stakeholders (those contributing to plastic pollution and potential change-makers) and passive stakeholders (those affected by the consequences of plastic pollution). By understanding the roles and interests of these stakeholders, more effective strategies to combat plastic pollution in the city can be developed.

1. Active stakeholders

Active stakeholders are those who directly contribute to the plastic pollution problem, as well as those who have the potential to drive change in this context. The following types of active stakeholders were identified: plastic industry, businesses and consumers, local government, educational institutions and environmental organisations. In 2019, Vietnam's plastic industry contributed $17.5bn to the national economy, equivalent to nearly 7 % of the gross domestic product (Snell (2022)). Businesses such as shops and restaurants contribute significantly to plastic pollution through single-use plastics, such as plastic bags, containers, and cutlery while consumers with their choices and their behaviours significantly impact the demand for single-use plastics.
The local governments and municipalities play a pivotal role in addressing plastic pollution. They can implement regulations, policies, and incentives to encourage businesses and consumers to adopt sustainable practices. Ho Chi Minh City authorities have proposed incineration and waste-to-energy conversion as a solution to the waste issue. This long-term plan aims to close landfills gradually and convert 80% of the city's waste into energy through incineration. Various waste-to-energy projects, such as the Vietstar Joint Stock Company plant and others, have been initiated, but several remain incomplete due to energy development and funding challenges. After a revision to Vietnam's Law on Environmental Protection went into effect this January, the country's municipalities were made responsible for sorting and recycling waste. But without enforcement or implementation, there continues to be no official recycling mechanism. In fact, across Vietnam, just 27% of the plastic waste generated each year is recycled (Snell (2022)).
A second key-change makers after governments is represented by educational institutions such as schools and universities that can actively engage in awareness campaigns and educational programs to instil a sense of environmental responsibility in the younger generation.
Environmental organizations and community initiatives are also active stakeholders: various small-scale initiatives and community groups, such as the Sai Gon Xanh team and the HCMC Water Environment Improvement Project, are actively involved in cleaning canals and other public spaces in the city.
In the active stakeholders' context, the mismanagement of waste, intricately linked with legislation, also pose a significant challenge. Despite the absence of an official recycling system in Ho Chi Minh City, "ve chai" or waste pickers constitute a driving force for recycling. These individuals earn small incomes by collecting plastic bottles, cardboard, and metal, selling them to informal recycling centers. However, substantial waste still ends up in landfills, unsorted or untreated, impacting the environment.

2. Passive stakeholders

Passive stakeholders are those who are indirectly affected by plastic pollution and may or may not be actively involved in creating change but still bear the consequences.
We firstly identified as passive stakeholders the flora and fauna: the natural environment, including plants and wildlife, suffers from the adverse effects of plastic pollution, leading to habitat destruction and harm to ecosystems.
The residents and general public of Ho Chi Minh City can be categorized as both active and passive stakeholders. These individuals face various health and quality of life challenges due to the pervasive plastic pollution in the city. Public health is adversely impacted, and the overall aesthetics and livability of the city are compromised. It is important to note that these effects are often more pronounced in less affluent districts, particularly those located away from the city center. During our stay, we observed firsthand that many families residing in stilt houses along the Saigon River are consistently exposed to plastic litter that flows through the river.
Finally a passive stakeholder is represented by the future generations who will inherit the consequences of plastic pollution making it crucial to educate and raise awareness among young people.

From our firsthand experience during our ten-week stay in Ho Chi Minh City, it is evident that efforts to mitigate plastic pollution are significantly lacking, if not entirely absent. Several key observations highlight this issue, starting with the widespread use of single-use plastic items by almost every shop.There are no regulations or policies in place, such as levying an additional charge for plastic bags, to discourage their use.
Moreover, the streets of Ho Chi Minh City are characterized by a multitude of markets and food stalls, yet there is a noticeable scarcity of public rubbish bins. This absence of proper waste disposal infrastructure exacerbates the problem, as residents and visitors alike struggle to find appropriate places to discard their waste. Consequently, the city is plagued by a significant volume of garbage, including a substantial amount of plastic litter that easily ends up in waterways and in the natural environment in general.

Effectively tackling the substantial problem of plastic pollution in Ho Chi Minh City necessitates a comprehensive approach involving active and passive stakeholders. Active stakeholders, encompassing businesses, consumers, government entities, educational institutions, environmental organizations, and waste management initiatives, can drive change by adopting sustainable practices and advocating for policy amendments. Simultaneously, the considerations of passive stakeholders — natural environment, residents, and future generations — are paramount when devising strategies to mitigate plastic pollution effects.
Fostering cooperation and shared responsibility among all stakeholders is fundamental in crafting lasting solutions to this pressing issue. Additionally, with Vietnam being a top contributor to ocean plastic pollution, national and international attention is vital, especially with the United Nations' ongoing efforts to create a legally binding instrument on plastic pollution.

Figure 4:
Plastic pollution in the Saigon River, Ho Chi Minh City, Vietnam.

6 Measurements and Data

6.1 Field Measurements

Measurements on the field were made throughout the whole month of September, 2023 over three bridges that cross the Saigon River in Ho Chi Minh City: Thu Thiem (10.786537, 106.717959), Binh Loi (10.824837, 106.709258) and Phu Long (10.890169, 106.692122).

We decided to study a system that consists of the stretch of the river starting from the Phu Long Bridge and ending in the Thu Thiem Bridge. By doing so, we considered a specific volume of control with an entrance at Phu Long, upstream of Ho Chi Minh City, and an exit at Thu Thiem, at the downstream end of the most populated part of the city. A further measurement location, the Binh Loi Bridge, has been chosen approximately in the middle of the volume of control to tackle what happens right in the middle of the city. Considering this stretch allowed us to measure hydraulic parameters, plastic transport and hyacinth abundance both upstream and downstream of the city, also to address how the plastic produced by the city influenced the overall pollution of the river. The considered study area is depicted in Figure 2.

To investigate the spatial cross sectional variability of the measured parameters, each bridge has been divided into 4 to 6 transects of different length. The lengths have been determined with the intent of minimizing the impact of the bridge piers. Measurements were taken in the middle of each transect, to have a good representation of the fluxes at each location. The duration of the different measurements depended on the availability of the surveyors, the set up of the instruments, the time taken to lower and take back the instruments in the water and the presence of boat traffic. Each measurement interval had a duration of 3 to 15 minutes. Approximately, 360 measurements have been carried out in the different transects of the bridges over 4 weeks in the month of September. Both sides of the bridges have been used for measuring, depending on the tidal regime. Measurements took place in the northern side of the bridge during flood tide and in the southern part during ebb tide. As an example, Figure 5 depicts the division of Phu Long Bridge into transects:

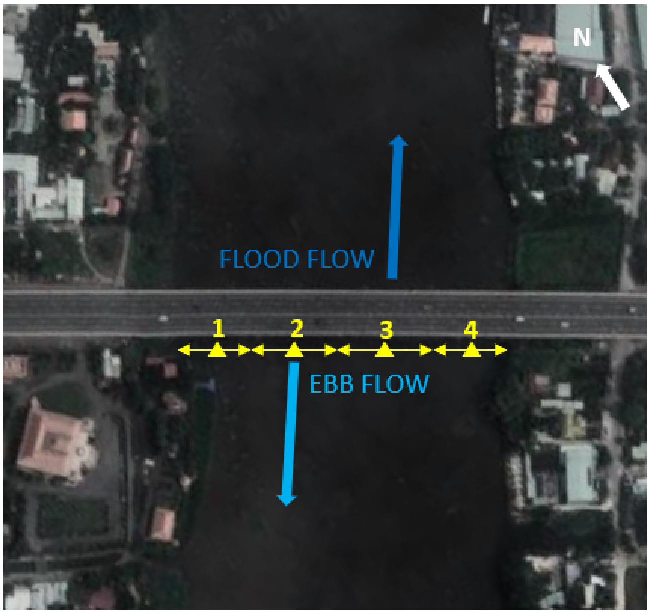


Figure 5:
Phu Long Bridge has been divided into 4 transects. In the middle of each transect (yellow triangle), measurements were taken. During ebb flow, measurements have been done in the southernmost side of the bridge. During flood flow, measurements have been done in the northernmost side.

We planned to organize the same quantity of measurements for both ebb and flood tidal phases. However, the only available data regarding the actual tidal phase at different locations is the water level variation charts provided by `https://tides4fishing.com`. Moreover, there is a time delay between the reversal of flow direction (slack water) and the reversal of the water level, which is on average 1 hours 36 minutes (Lotcheris et al.

(2023)). This time delay varies daily and at different locations. Therefore, it is not possible to foresee the tidal phase precisely without going to the bridges. In addition to this, the rising of water level, hence flood tide, has on average a lower duration than its falling: respectively 10 hours, 52 minutes for rising water level and 13 hours, 08 minutes for falling water level in the month of September, 2023. For these reasons, more data was obtained for ebb tidal phase than for flood tidal phase. For future studies, we suggest to perform a tidal analysis to address the influence of each main tidal component.

At each measurement location, the following measurements have been conducted:

- Free surface flow velocity
- River depth
- Number of floating plastic passing through the transect over a 130 seconds period
- Number of plastic entrapped in floating hyacinths passing through the transect over a 130 seconds period

As a reference, Table 1 shows the example of one day of measurements taken at Binh Loi Bridge. The table shows how data collection was organized. Data analysis was done after the measurements and is presented in the following sections. The table shows that six rounds of measurements were organized every day and during each round, measurements were repeated at the different bridge transects. In the table, FFP indicates Free-Floating plastic items passing the observation point over a 130 seconds period, while EP denotes the hyacinth-Entrapped Plastic items.

Table 1: Measruements gathered on September 12, 2023 at Binh Loi Bridge.

Binh Loi Bridge, 12 September 2023, Ebb tide

Time	Transect	FFP [items]	EP [items]	$\mathbf{v}_{nearsurface}[m/s]$	depth [m]
08:23	**1**	0	0	0.1	4.4
08:26	**2**	0	0	0.1	17.6
08:29	**3**	0	0	0.3	19.5
08:32	**4**	4	1	0.3	8.4
08:35	**5**	1	31	0.1	1.1
08:40	**1**	0	0	0.1	4.2
08:43	**2**	1	0	0.2	16.7
08:46	**3**	0	0	0.3	19.3
08:49	**4**	7	19	0.3	7.9
08:51	**5**	7	5	0.1	0.8
08:58	**1**	0	0	0.1	4.1
09:01	**2**	0	0	0.2	16.8
09:03	**3**	1	0	0.3	17.9
09:06	**4**	1	0	0.3	8.5
09:08	**5**	13	3	0.1	0.8
09:14	**1**	0	0	0.1	4.4
09:17	**2**	0	0	0.3	16.8
09:20	**3**	0	0	0.3	19.4
09:25	**4**	10	2	0.3	9.1
09:27	**5**	8	3	0.1	0.6
09:31	**1**	0	0	0.1	4.4
09:33	**2**	0	0	0.2	16.9
09:35	**3**	0	0	0.3	16.6
09:38	**4**	5	0	0.3	8.6
09:41	**5**	7	4	0.1	0.8
09:45	**1**	1	0	0.1	4.3
09:47	**2**	0	0	0.2	17.5
09:50	**3**	1	0	0.3	18.9
09:52	**4**	5	0	0.3	7.6
09:54	**5**	6	1	0.1	0.9

6.2 Flow velocity and water depth measurements

Flow velocity and water depth were measured in the middle of each bridge transect. Near surface flow velocities were measured using a propeller flow meter (Flowatch JDC, `https://www.jdc.ch`). The flow meter was lowered from the bridge using a 30 m long hanging sensor. By marking the rope , we made sure that the flow velocities were always measured at the same depth: namely 10 cm below the water surface. Flow velocities were considered positive for ebb flow and measured from the southern side of the bridges, while negative values were assigned to flood velocities that were measured from the northern side of the bridges. To obtain a stable result, the flow meter has been kept still below the water surface for half a minute during each measurement. The sensitivity of the instrument is 0.1 m/s, with minimum detectable magnitude of 0.0 m/s. Due to the limited precision of the instrument and the fact that flow velocities are on average low for this stretch of the river (Camenen et al. (2021)), we observed a small variations in data, ranging from magnitudes of 0.0 m/s to 0.5 m/s.
To estimate the depth-averaged velocity, the free surface flow velocity was multiplied by a coefficient of 0.85, normally used in natural channels (Costa et al. (2000)).

Water depth was measured using a single beam sonar with Compressed High Intensity Radiated Pulse (CHIRP) (Deeper Smart Sonar Chirp 2, https://deepersonar.com). The sonar was lowered from the bridges using a 30 m long rope. Once the sonar reached the water surface, water depth value was displayed by the Fish Deeper application, directly connected with the instrument. To have a stable value of the measured depth the sonar was kept floating in the river up to 2 minutes long.

With the measured values of water depth and flow velocities at each transect, we could calculate the water discharge for each river cross section using the same approach as Schreyers et al. (2023).

We first computed the cross sectional area of each river segment as follows:

$$a_i = w_i \cdot d_i \tag{1}$$

with d_i the measured river depth [m], w_i the length of the considered transect. By doing so, we assumed that each transect of the river could be approximated with a prism.

The cross sectional water discharge [m^3/s] of a single river section was measured as follows:

$$Q_i = a_i \cdot v_i \tag{2}$$

with v_i the depth-averaged velocity.

Every day of measurements was dedicated to a single bridge, and 6 measurements have been done at each location at different times within intervals of approximately 3 hours a day, to account for temporal variability of the river discharge. For each transect, a box plot has been built every day to visualise the variability of the discharge measurements (Figures 18, 19, 20). The median discharges of each river section have been added together to derive the total cross sectional river discharge.

6.3 Plastic measurements

During each flow velocity and depth measurement, a visual counting of the flux of plastic has also been carried out using the method developed by González Fernández and Hanke (2017). From the measurement location, a camera (SMC Pentax-DA 35mm F2.8 Limited Macro) has been placed over the river for a duration of 130 seconds per measurement. The camera settings allowed us to take pictures at regular intervals of 10 seconds. At each transect a set of 13 images was obtained for each round. The plastic was divided in free floating plastic items and plastic litter entrapped in water hyacinths. Every litter that was even slightly in contact with a water hyacinth was considered to belong to the second category. In fact, we could easily notice that if plastic is barely touching a hyacinth and flowing with it, it likely tends to stay entrapped also many meters away from the observation point. It was assumed that these items would remain entrapped over a long term period of the river flow. Plastic items were later categorized in the following classes: EPS (expanded polystyrene such as food packaging), PO hard (hard polyolefins, such as bottle caps), PO soft (soft polyolefins, e.g.: shopping bags and foils), PS (polystyrene, such as plates), PET (e.g.: plastic bottles), multilayer plastic (food wrappers) and with the voice “other” we defined all the plastic items that were not easy to identify (e.g.: too small or too ruined pieces). This method allowed to count visible (>2.5 cm) anthropogenic litter items down to 10 cm

below the water surface. It is important to take into account that visual observations may be compromised by weather conditions, sun orientation, the height of the observation point and plastic categories.
In fact, the weather conditions during the measurements were extremely variable both daily and also within the intervals of measurements (approximately 3 hours). The alternation of sunny, covered sky and mild rains during the measurements certainly influenced the lighting of the pictures and the ability to identify all the pieces of floating plastic. Some pictures were completely or partially covered by sunlight and could not be used.

This method allowed us to count the items of plastic flowing through the observation point in a 130 seconds minutes interval. These quantities were then converted into plastic flux estimates using the formula introduced by Schreyers et al. (2023).

To obtain the plastic transport expressed in *items/hour*, the mean plastic transport observation was first calculated for each bridge transect:

$$f_i = \frac{N_{ff,i}}{t_{ff,i}} + \frac{N_{e,i}}{t_{e,i}} \tag{3}$$

With $N_{ff,i}$ the number of free floating plastic items and $N_{e,i}$ the number of hyacinth-entrapped plastic items, both counted for each observation point i. All the observations were done over a 130 seconds interval expressed by $t_{ff,i}$ for the free-floating items and by $t_{e,i}$ for the entrapped items.

Total floating plastic transport F_i [*items/hour*] was obtained for every round covering the entire as follows:

$$F_i = \sum_{1}^{n} \frac{f_i}{w_i} \cdot W_i \tag{4}$$

With w_i the width of the observation segment W_i the total width of the river cross section, and n the number of transects. The average of the 6 rounds was then computed.

Note that we classify plastic flux F [*items/hour*] as the total amount of plastic items that flows trough the river top cross section in one hour. By river top cross section we mean an area that extends in length from bank to bank, and in depth down to the the first visible 10 centimeters. The flux was hence defined as total cross sectional floating plastic flux and not as plastic flux per m^2. This choice was made so that our values could be confronted with data that are available in literature and that consider the same stretch of the Saigon River also calculating a total cross-sectional floating plastic flux.

The above described procedure was repeated in order to calculate not only the total plastic flux, but also the free-floating plastic flux and the hyacinth-entrapped plastic flux separately.

6.4 Net quantities estimates

The Saigon River is a semi-diurnal tidal system in which ebb and flood tides alternate. As a consequence, river discharges and plastic fluxes can instantaneously be either seaward directed (during ebb tide) or landward directed (during flood tide). Net river discharge and net plastic flux are defined as net tide-averaged quantities that are the result of the succession of ebb and flood tidal phase and the inversion of direction of water and plastic flux. It is important to determine net quantities of plastic flow, since they could give a first estimate of the plastic quantities that are actually flowing towards the sea. For this purpose, we utilized the approach introduced by Schreyers et al. (2023), with some differences given by our limitations. In fact, our measurements were not continuous over entire tidal cycles due to the impossibility to leave the instruments fixed at the measurement locations for periods of entire tidal cycles, and also to stay long periods of the day in the field, due to very hot weather conditions.
Instead, we organized measurements three days a week for four weeks for about 3 hours each day in the morning, as explained in Section 6.1. Measurements were organized at approximately the same time everyday in the morning. By doing so, we could obtain a fairly wide data set that accounts for different tidal phases. Moreover, lack of available data made it not possible to reconstruct the hydrograph of the river system. Therefore, our measurements were randomly taken over the hydrological cycle of the river, with no distinction between base and peak flow.

We have first calculated the net water discharge for the month of September. Firstly, to calculate average volume of seaward/landward directed flowing water [m^3], the following formulas introduced by Schreyers et al. (2023) have been used:

$$V_{w,ebb} = Q_{av,ebb} \cdot T_{ebb} \tag{5}$$

$$V_{w,flood} = Q_{av,flood} \cdot T_{flood} \tag{6}$$

where $Q_{av,ebb}$ and $Q_{av,flood}$ are the average ebb and flood discharges over the entire river cross section, while T_{ebb} and T_{flood} are respectively the duration of the ebb and flood tidal phase.

Subsequently, the average net discharge has been estimated with the following formula:

$$Q_{net} = \frac{V_{w,ebb} + V_{w,flood}}{T_{ebb} + T_{flood}} \tag{7}$$

A phase shift between minimum flow velocity and maximum water level exists and has been estimated to be around 1 hour and 36 minutes in the Saigon river (Lotcheris et al. (2023)). To account for the effect of this tidal asymmetry, 1 hour and 36 minutes have been added to both the duration of falling and rising water, which has been calculated with the tidal charts accessible online. We could also witness one event of High Water Slack: tide reversal from flood to ebb tide on September, 20 at Phu Long Bridge. During slack water, flow reverses and the velocity measured close to the river surface approaches 0.0 m/s. On this day, we roughly estimated the duration of slack tide by calculating the time difference between the moment when the river top cross section (down to 10 cm) was completely still, to the moment when it started flowing in the opposite direction. The estimated duration of slack tide was 24 minutes. During the period of slack tide, plastic litter and water hyacinths were not moving or showing little and slow movement. Right after flow reversal, they started moving again in the opposite direction than before.

The duration of ebb and flood tidal phases was finally estimated by taking an average of the duration of high water and low water for each day over the month of September, adding the average phase shift duration (1 hour 36 minutes) and removing the duration of slack water as estimated through our observations (24 minutes). This results in the following average ebb and flood period, for the month of September, 2023:

T_{ebb}= 14 hours 20 minutes
T_{flood}= 11 hours 4 minutes

A net discharge of 240.86 m^3/s has been obtained with our measurements, which is similar to values available in the literature for the same month (Van Emmerik et al. (2019)).

In a similar way, the net plastic flux for the month of September was calculated by first estimating the total ebb and flood plastic flux volumes [*items*] as follows:

$$V_{p,ebb} = F_{av,ebb} \cdot T_{ebb} \tag{8}$$

$$V_{p,flood} = F_{av,flood} \cdot T_{flood} \tag{9}$$

with $F_{av,ebb}$ and $F_{av,flood}$ respectively the average estimated plastic flux during ebb and flood phase.
The average net plastic flux has been estimated with the following formula:

$$F_{net} = \frac{V_{p,ebb} + V_{p,flood}}{T_{ebb} + T_{flood}} \tag{10}$$

A net seaward directed plastic flux of $1.09 \cdot 10^4$ *items/hour* was obtained for the month of September, which is twice as high as what estimated by Van Emmerik et al. (2019) for the same month in 2019. We believe that such an increase in the flux could be addressed to the high rate of population growth, and as a consequence plastic

production, of the city. In fact, Ho Chi Minh City experienced an increase in population of about 1 million within the last 5 years (Macrotrends (2023)).
A big limitation of this approach is that measurements are not continuous over the tidal cycle. However, water level charts suggests that the tidal phase was different every day at the same time, thus allowing us to analyse both ebb and flood tides measurements. A tidal constituent analysis, or a continuous monitoring campaign of discharge values over entire tidal cycles would be a big implementation that is recommended for further studies.

6.5 Rainfall data

To gain a better understanding of how rainfall influences plastic transport in the Saigon River, obtaining daily precipitation data was essential. Given that Ho Chi Minh City is located on the Southeast Asian monsoon belt, characterized by distinct wet and dry seasons, comprehending how seasonal variations in rainfall can affect plastic transport was also critical.

To extend our study over a longer timeframe, we used a dataset of plastic measurements encompassing a period of 9 months, from August 15, 2020 until April 17, 2021. The measurements were taken only at one location, namely Binh Loi Bridge. By using this data set, plastic fluxes were obtained for both the wet and dry season, thus allowing us to make conclusions on the seasonality of plastic fluxes. Our local collaborator, Mr. Le Thanh Khiet Bui together with colleagues, already collected plastic measurements during the period from August 2020 to April 2021 using the same approach followed by us in our project. Binh Loi Bridge was divided into 6 transects, each with a length of approximately 25 m. The interval adopted by the research group to count the items of plastic flowing through the observation point was 10 minutes. By using the formulas developed by Schreyers et al. (2023), which were extensively explained in Section 6.3, we were able to compute the plastic fluxes at Binh Loi Bridge from August 2020 until April 2021. Only after checking that the results from the measurements taken in September 2023 and those taken from August 2020 to April 2021 were consistent, we started to make correlations and comparisons between the data. This dataset, which comprehends a longer period of time, allowed us to obtain valuable insights into seasonal variations of plastic pollution in the Saigon River.

To obtain daily rainfall data, we used the hourly precipitation maps provide by Global Precipitation Mission (GPM), which is a satellite mission led by NASA and the Japan Aerospace Exploration Agency (JAXA) (`https://www.eorc.jaxa.jp`).
When collecting the rainfall data, we selected an area sufficiently large to encompass both the bridge and its surrounding vicinity. Precipitation values are recorded on an hourly basis, presented as intervals with lower and upper bounds. To simplify our analysis, we computed the average between these bounds, which proved adequate for our research objectives. This method allowed us to obtain daily rainfall values, spanning from midnight of the selected day to midnight of the following day. We applied the same approach approach for September 2023 and the longer period spanning from August 2020 to April 2021.

7 Results and Discussion

In this section we present the results of our analysis. We first address the variables that influence plastic transport in the Saigon River. Among others, we focus on rainfall, river discharge, tides and the effect of water hyacinths. An analysis on plastic composition and plastic distributions over the study area is also presented.

Table 2 presents a summary of the measurements. Although measurements were repeated multiple times at different transects of the bridges every day, here we only present average daily values for the entire river cross section. In the table, we only present the measurements that have been used for the study. Here we only show the average values as obtained daily in the field and not the median values that have been obtained subsequently, which can be observed in Figures 18, 19, 20. More measurements were taken, especially in the first weeks, however some mistakes in the field resulted in non-reliable data that were excluded from the study.

Table 2: Measurements and data: average discharge and plastic flux values

Date	Location	Tidal Regime	$Q_{av}[m^3/s]$	$F_{av}[items/hour]$
06/09	Binh Loi	ebb tide	630.47	41961
09/09	Thu Thiem	ebb tide	385.66	13227
12/09	Binh Loi	ebb tide	606.60	22065
19/09	Binh Loi	ebb tide	490.26	35273
20/09	Phu Long	flood tide	-140.25	-12691
20/09	Phu Long	ebb tide	105.85	28618
21/09	Thu Thiem	ebb tide	476.26	33960
26/09	Binh Loi	ebb tide	601.69	40677
27/09	Phu Long	ebb tide	415.36	7341
28/09	Thu Thiem	ebb tide	929.97	39213

7.1 Relation between rainfall and plastic flux

The aim of this section is to confirm our hypothesis, according to which rainfall can be considered as one of the factors influencing the plastic transport in the Saigon River. As already mentioned in Section 6.5, the rainfall data, both for the nine-month period dataset and the September 2023 dataset, was gathered from the hourly precipitation maps from Global Precipitation Mission (GPM).
Figure 6 shows a bar graph with the monthly rainfall distribution from August 2020 to April 2021. The monthly rainfall distribution exhibits a clear seasonality, demarcating the months of the wet season from those of the dry season. August, September, October, and November fall into the wet season, collectively gathering the 84.2% of the total rainfall for the nine-month period. Rainfall records in the remaining months sum up to 249.1 *mm*, accounting for the 15.8% of the rainfall for the whole period.

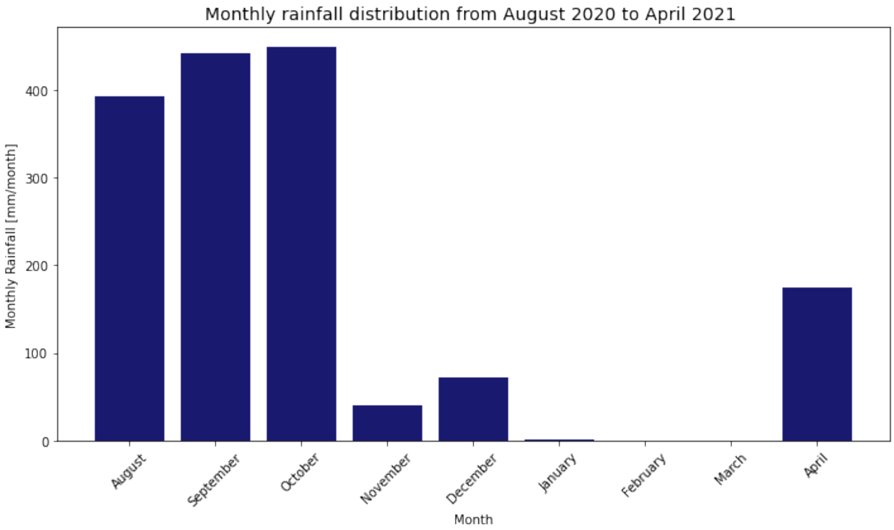
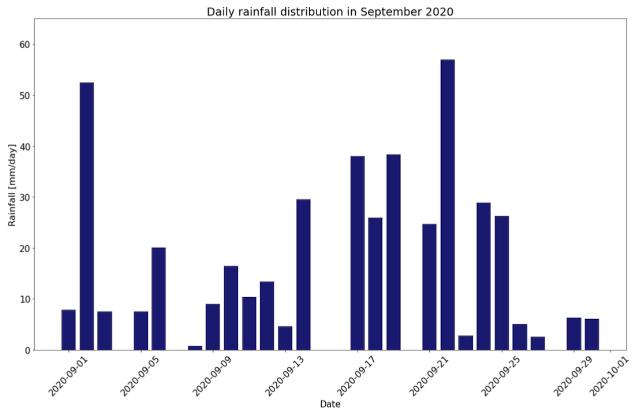
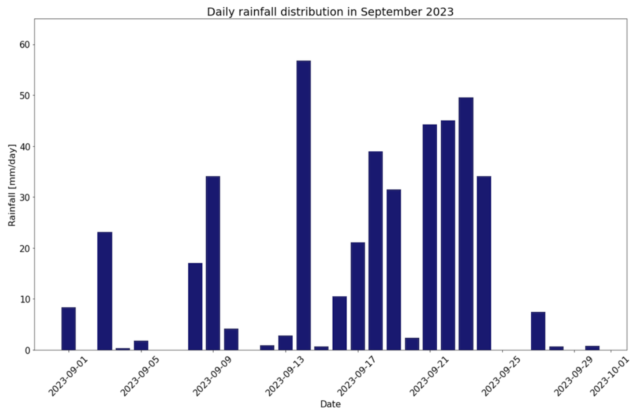


Figure 6:
Monthly rainfall distribution during the period from August 2020 to April 2021 at Binh Loi Bridge.

Figure 7 displays the daily rainfall distribution in the months of September 2020 and September 2023. The monthly recorded rainfall in September 2020 was 441.8 $mm/month$, while in September 2023 it was 436.0 $mm/month$. Almost the same number of rainy days were recorded in the two periods, with September 2020 having 24 rainy days and September 2023 having 23 rainy days.



(a) Daily rainfall distribution in September 2020.



(b) Daily rainfall distribution in September 2023.

Figure 7:
Daily rainfall distribution for the two months of September at Binh Loi Bridge.

As already mentioned in section 6.5, the rainfall data from GPM was obtained by taking the average of the upper and lower bounds of an hourly interval. Taking this into consideration, we recognized that this averaging might introduce an uncertainty, which we sought to quantify.
To assess this uncertainty, the standard error (SE) associated with averaging the upper and lower bounds was calculated. The standard error was defined as:

$$SE = \frac{R}{4} \tag{11}$$

This estimation is a simplistic representation of variability within the range, and it assumes that the entire range has an equal likelihood of occurrence. We opted for this definition of the standard error as it is difficult to make any assumption on the distribution of the data, having only two one upper and one lower bound. We applied the formula for each hourly interval obtaining the hourly standard errors. Assuming that the hourly standard errors are independent, we simply summed them to obtain a daily value that represents the uncertainty introduced by the process of averaging hourly intervals for a single day.
For the monthly data, we aggregated the daily errors by summing them to obtain a cumulative uncertainty.

Figure 8 displays the monthly distribution of rainfall with the uncertainty bars indicating the monthly standard errors.

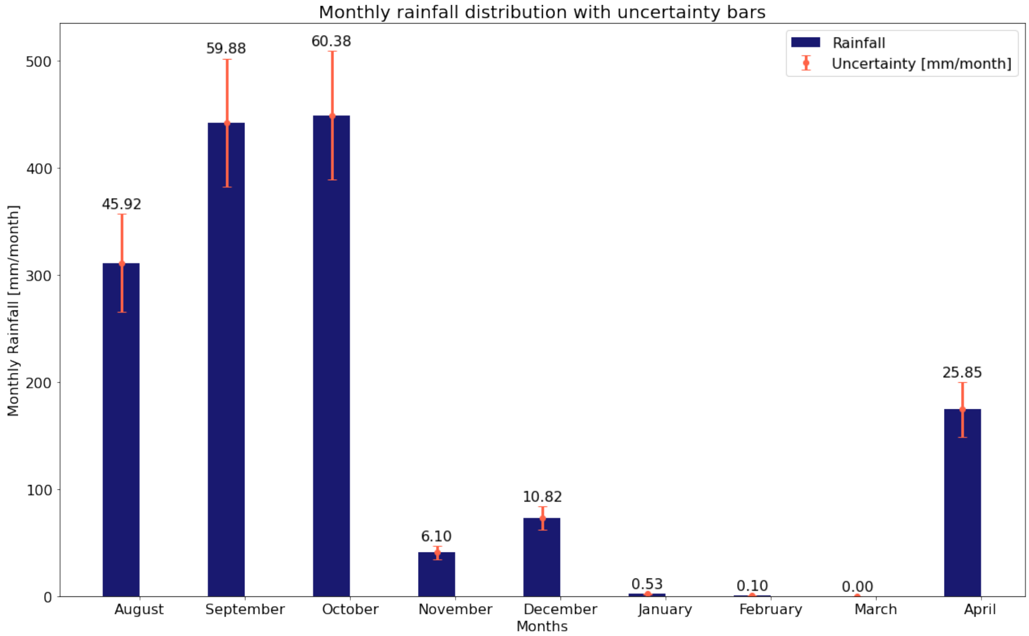
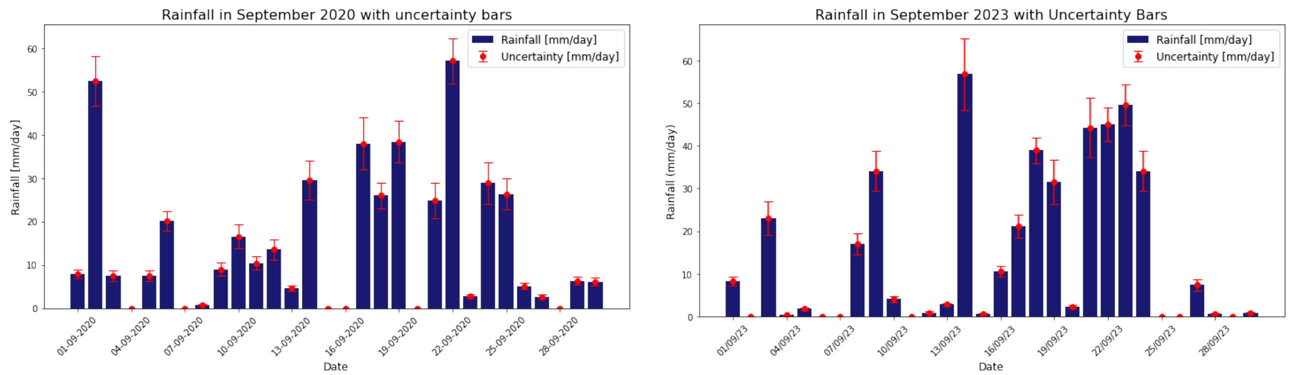


Figure 8:
Monthly rainfall distribution from August 2020 to April 2021 at Binh Loi Bridge with uncertainty bars.

Figure 9 shows the daily standard errors calculated for the months of September 2020 and September 2023.



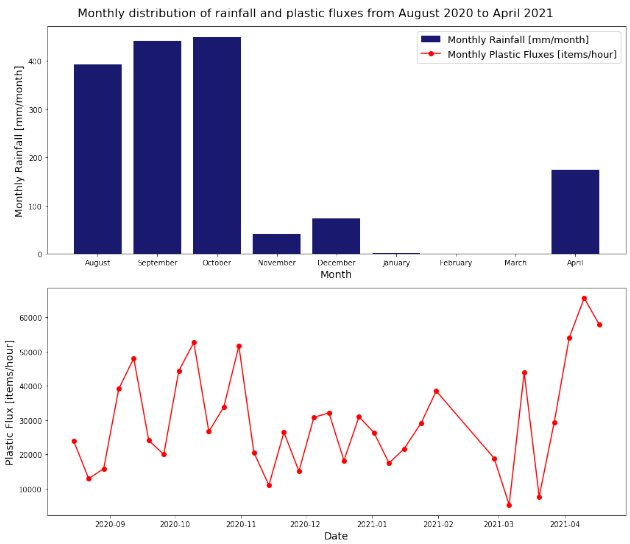
(a) Daily rainfall distribution in September 2020 with uncertainty bars.

(b) Daily rainfall distribution in September 2023 with uncertainty bars.

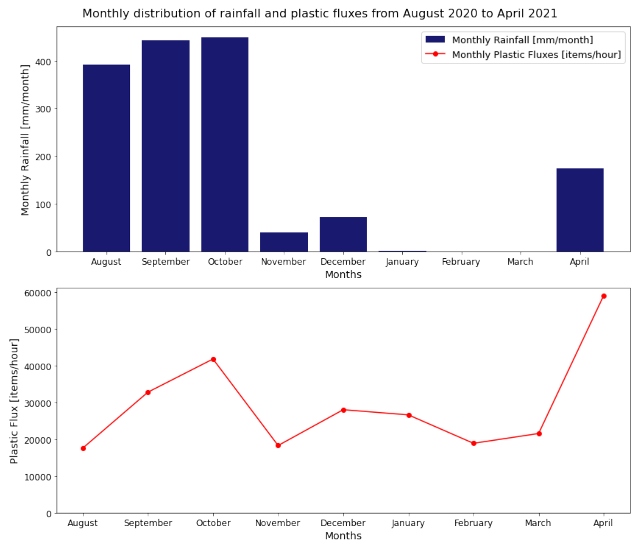
Figure 9:
Daily rainfall distributions in September 2020 and September 2023 with uncertainty bars.

After visualizing the rainfall distribution for both periods considered in our analysis, we went on to plotting the distribution of plastic fluxes.
The research team who did the visual counting of plastic from August 2020 to April 2021 collected these measurements every Saturday of the month. This means that for each month there are four to five measurements, excluding the month of February where only one day of measurements was carried out. Also, the visual counting of plastic at Binh Loi Bridge started August 15, 2020 and ended April 17, 2021, meaning that less data is available for the months of August 2020 and April 2021.
The line graph in Figure 10a displays the plastic fluxes for the period extending from August 2020 to April 2021. Given the fact that measurements were taken only once a week and therefore our data is limited, recognizing a distinct trend in plastic fluxes proved to be challenging. The graph shows a lot of fluctuations between lower and higher plastic flux values. Nevertheless, it is worth noticing that the values of plastic flux tend to be higher

during the months belonging to the wet season, suggesting a possible seasonality in plastic fluxes in the Saigon River.
To check for the presence of a seasonality in the plastic fluxes, we computed the means of the plastic flux values for both the wet and the dry season, obtaining 31874 $items/hour$ and 25011 $items/hour$ respectively. Subsequently, we conducted a t-test on the means of the plastic fluxes to determine whether there was a statistically significant difference in plastic transport during the two seasons. The t-statistic was found to be 1.40, whereas the p-value associated with the t-test was 0.17, which is more that the significance level alpha of 0.05. Therefore, the t-test revealed no significant difference in the means of the plastic fluxes during the two seasons, implying that our data does not provide enough evidence to conclude that the means of the two groups are different. This might be caused by the small group of data available, with only 29 plastic flux values available for the nine months considered for both the wet and the dry season. Nevertheless, both previous studies (Van Emmerik et al. (2019)) and the results showed in the forthcoming sections suggest that a difference in the plastic fluxes between the wet and dry months exists.
To gain a more comprehensive understanding of the monthly plastic fluxes, we also plotted the monthly distribution of plastic fluxes as displayed on the graph of Figure 10b. Notably, April stands out with a significant increase in monthly plastic fluxes. This significant increase could be attributed to the absence of two days of measurements, as data collection ceased April 17, 2020. This data gap likely contributed to the substantial upswing observed in the month of April. Conversely, the lower values recorded for August could have been caused by the fact that only three measurements were taken during the month.



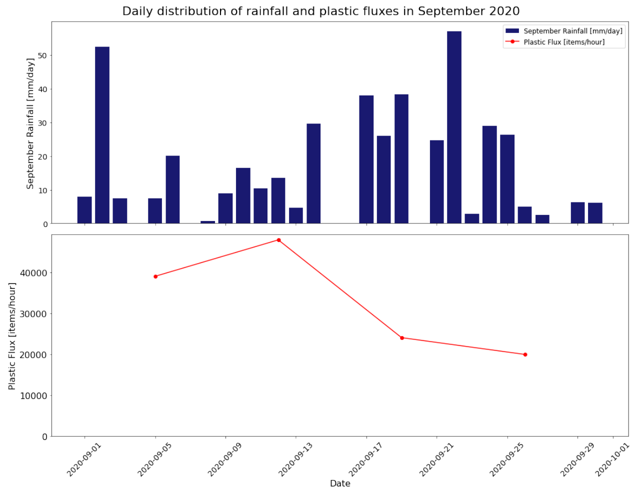
(a) Monthly rainfall distribution and daily distribution of plastic fluxes from August 2020 to April 2021.



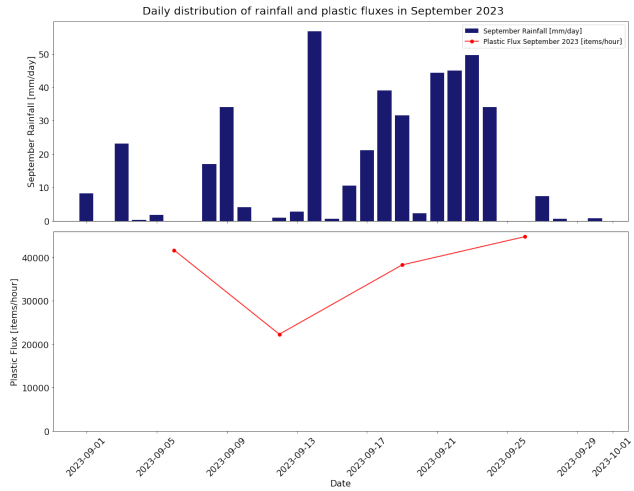
(b) Monthly distribution of rainfall and of plastic fluxes from August 2020 to April 2021.

Figure 10:
Daily and monthly plastic fluxes from August 2020 to April 2021 at Binh Loi Bridge.

Figure 11 below shows the plastic distribution for the months of September 2020 and September 2023. Again, plastic counting took place at Binh Loi Bridge only four times during both the month of September 2020 and September 2023. From a first visual analysis, plastic fluxes and rainfall do not seem to be correlated in the two months of September.



(a) Daily distribution of plastic fluxes at Binh Loi Bridge in September 2020.



(b) Daily distribution of plastic fluxes at Binh Loi Bridge in September 2023.

Figure 11:
Daily distribution of rainfall and plastic fluxes in September 2020 and September 2023 at Binh Loi Bridge.

Following the initial visual examination, we proceeded to conduct a correlation analysis to identify whether a relationship existed between the rainfall data and plastic fluxes, as well as to assess the strength of this relationship. Given the uncertainty on the distribution of plastic flux data, we opted for the Spearman's rank correlation. Spearman's rank correlation coefficient is indeed a non-parametric test that does not rely on data distribution assumptions. To understand whether rainfall influences monthly variations in plastic fluxes, we computed the Spearman's rank correlation coefficient obtaining a positive weak correlation (ρ = 0.27, p = 0.12, confidence interval = (-0.0781, 0.5632)). This implies that there is no significant relationship between the plastic fluxes and the rainfall.
We further categorized the monthly data into two distinct seasons: the wet season, encompassing August, September, October, and November, and the dry season, consisting of December, January, February, and March. Subsequent computation of the Spearman's rank correlation coefficient revealed a positive moderate correlation (ρ = 0.56, p = 0.02, confidence interval = (0.0955, 0.8284)) between the plastic fluxes in the wet season and the corresponding wet season rainfall. This could suggest that there could be a more pronounced correlation between rainfall and plastic fluxes during periods with higher rainfall frequency and rainfall intensity.

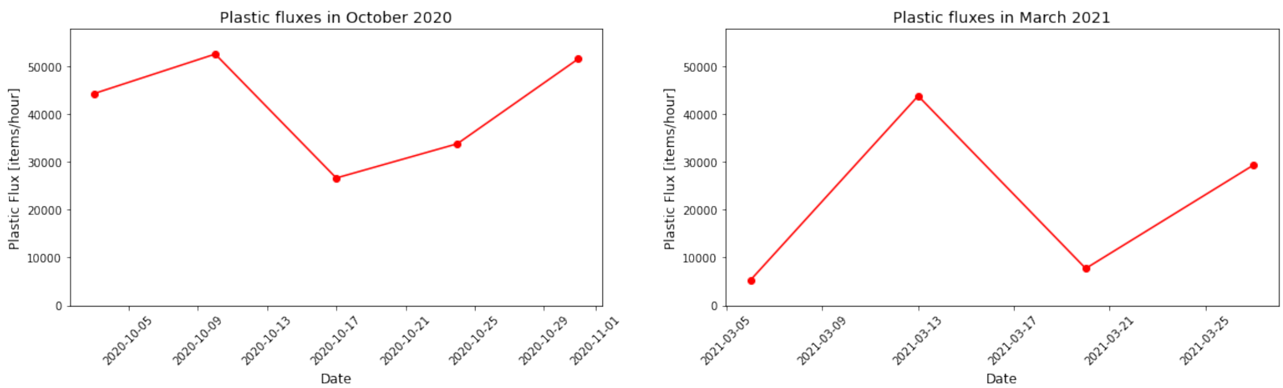
Previous research have already investigated the monthly correlation between rainfall and plastic fluxes in the Saigon River. In Van Emmerik et al. (2019), researchers addressed the seasonal variations in plastic transport over a period of ten months from March 2018 to December 2018. Measurements were taken at Thu Thiem Bridge and the same methodology for the visual counting of plastic adopted by us was followed. Their analysis involved calculating the correlation between plastic transport and rainfall using Pearson's correlation coefficient, which produced a result suggesting no correlation (Pearson's r = -0.34, p = 0.34).
In Van Emmerik et al. (2019), the rainfall data was obtained from a local weather station, the Mac Dinh Chi Station, located in District 1 in Ho Chi Minh City. The data is made openly available by the Ho Chi Minh Irrigation Management Company (`http://www.dichvuthuyloi.com.vn`). Knowing that our data is affected by some uncertainty due to averaging between the upper and lower bounds of a range, we reckoned it could be interesting to observe whether our results could change if we sourced the rainfall data differently. Therefore we also tried to use the data from the Mac Dinh Chi weather station for our two datasets. Note that, apart from this comparison, the results of our analysis were always obtained by using the data from GPM.

Since a more in-depth analysis on the differences between GPM and the Mac Dinh Chi weather station is not essential for our analysis, the results obtained by plotting the data from the weather station are included in Section 12.1. Within this section, we present graphs and delineate the primary distinctions in the data sourced from both GPM and the weather station. We concluded that the Mac Dinh Chi weather station does not always provide an accurate estimate of the daily rainfall distribution. Also, the weather station is located at approximately 4.5 km from Binh Loi Bridge, meaning that it probably does not give an accurate value of precipitation for the area where the bridge is located. Furthermore, it only provides a point estimate at its specific location.

When understating the correlation between rainfall and plastic fluxes, it could be more useful not to look only at the exact location of the bridge, but also part of the area surrounding it. Given the fact that GPM provides an averaged value of a larger area, it might provide more valid data. We therefore confirmed that GPM is more reliable when carrying out this kind of research.

Following our correlation analysis of the monthly variations in plastic fluxes, we went on to investigate the relationship between the daily rainfall values and daily plastic values. For our investigation we considered the months of September 2020 and September 2023, allowing us to check for similarities in the relationship between rainfall and plastic transport during this month of the year. We continued to employ the Spearman's rank correlation coefficient as the assumptions previously made remained unchanged.
Determining the time lag between a rainfall event and its possible influence on plastic fluxes proved to be particularly challenging. Given the complexity of the Saigon River's dynamics, it is difficult to identify a value for this time delay which could be used in our analysis. In Camenen et al. (2021), it is suggested that during the wet season, the response of the hydraulic system to rainfall can be more direct and immediate due to the heightened intensity and frequency of rainfall events. Taking this into consideration, we introduced an offset spanning from a day to a week. This means that we looked at the daily rainfall values up to seven days before the plastic measurement was taken, allowing us to further investigate a possible relation between rainfall and plastic fluxes.
However, we observed large variations in the Spearman's rank correlation coefficient both in its magnitude and its sign. We therefore concluded that rainfall cannot be considered to have a direct influence on the plastic transport in the Saigon River on the shorter scale.

What emerged as a more intriguing focus is understanding how plastic fluxes vary in periods of no rain and periods characterized by many days of rainfall. Given the fact that four to five plastic measurements are only available for each month, we chose to qualitatively investigate the plastic fluxes during one month of the wet season and one of the dry season, specifically in October and in March.
Figure 12 shows the daily distribution of plastic fluxes and rainfall in October 2020 and in March 2021.



(a) Daily distribution of plastic fluxes at Binh Loi Bridge in October 2020.

(b) Daily distribution of plastic fluxes at Binh Loi Bridge in March 2023.

Figure 12:
Monthly distribution of plastic fluxes in October 2020 and March 2021.

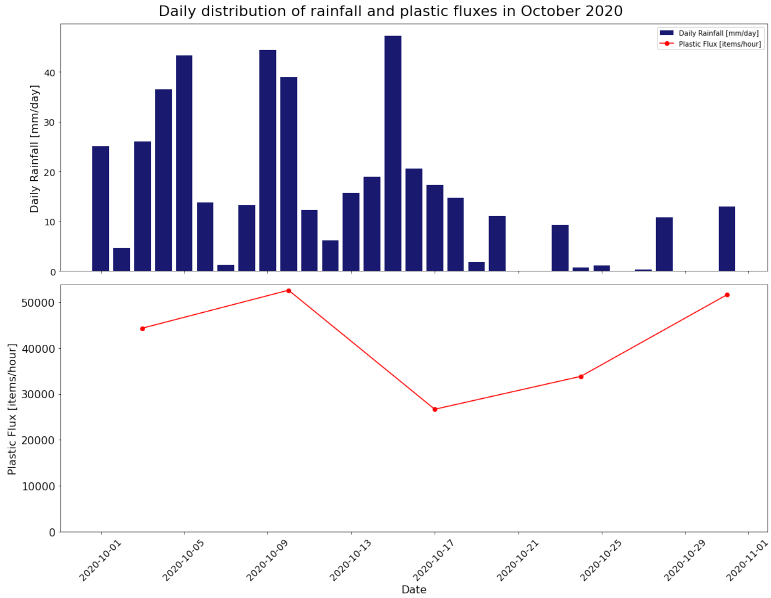


Figure 13:
Monthly rainfall distribution and daily plastic distribution in October 2020.

The month of October is particularly interesting as the first half of the month witnessed more frequent rainfall, including days with heavy rainfall. Conversely, the second half of the month experienced drier conditions. During the month of October, we had data for plastic fluxes available for only five days.
On October 17, 2020, just two days after a heavy rainfall event and following weeks of wet days, the lowest plastic flux value for the entire month was recorded. This proves that there is no direct correlation between rainfall and plastic transport, as already suggested above. In the latter part of the month, we observed higher values of plastic fluxes, further suggesting that rainfall does not play a significant role on the shorter timescale. When looking at the month of March, we noticed that some of the values on the graph are lower compared to the ones observed in October. This is consistent with the distribution of plastic fluxes observed in Figure 10 where lower plastic values were generally recorded during the dry season. It is worth noticing that, although two high values occurred, both instances took place during a period where it did not rain. This highlights the idea that other factors beyond rainfall exert an influence on plastic transport, especially on the shorter time scale.

In conclusion, our analysis revealed that there is no direct correlation between rainfall and plastic fluxes in the Saigon River, thus disproving our initial hypothesis. Other factors, such as river discharge, water hyacinth coverage and tides, are thought to have an influence on the transport of plastic in the river and will be further discussed in the forthcoming sections. Nevertheless, rainfall has a direct influence on tide-averaged water level and discharge, thus acting as an indirect factor on plastic fluxes in the Saigon River.
In fact, the tide averaged water level has been shown to follow the rain pattern for both increasing and decreasing phases, with a shift of approximately 2-3 months. Also the net discharge shows to be higher in wet months than in dry ones, as can be seen in Figure 14 (Camenen et al. (2021)). Therefore, a relation between rainfall and both discharge and water level exists. Comparing the net plastic flux that we obtained from our measurements, which amounts at $1.09 \cdot 10^4$ *items*/*hour* with other studies, allowed us to understand how much the rainfall could act with an indirect influence on plastic fluxes. Our value is about 3 times larger than the net plastic flux derived by Schreyers et al. (2023) right at the beginning of the wet season (beginning of May). In this case, we suppose that the increase in the tide-averaged river water level that characterizes the wet season is responsible for picking up a huge quantity of plastic that is normally deposited on the river banks or in the river floodplain. Plastic that is deposited on the river banks may come from run-off, wind transport, or plastic deposited after drop of water level, amongst others.

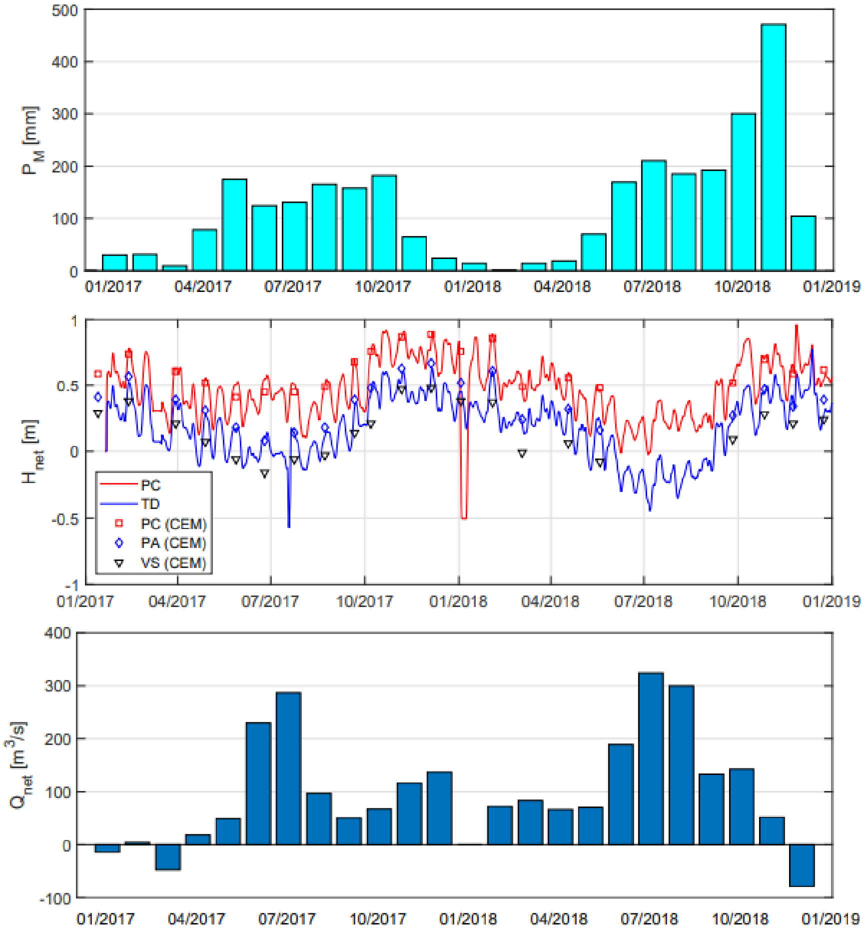


Figure 14:
Monthly rainfall (P_M), tide-averaged water level (H_{net}) and net water discharge (Q_{net}) over a two years period (Camenen et al. (2021)).

7.2 Effect of tides in plastic flux and horizontal distribution of plastic

The Saigon River is a tidal system characterized by a semi-diurnal tidal regime.
Throughout our observations, we observed dominant seaward or landward transport across the river cross-section. Nevertheless, we did note instances of reverse flow in specific locations, particularly during slack water, a phenomenon also documented by Schreyers et al. (2023).

By taking the average of all the daily estimated plastic flux, as highlighted in Section 6 we obtained the following values for the month of September:

$F_{av,seaward} = 2.91 \cdot 10^4 \; items/hour$
$F_{av,landward} = -1.27 \cdot 10^4 \; items/hour$

which results in a net seaward directed plastic flux of $1.09 \cdot 10^4 \; items/hour$.

The alternation of ebb and flood flow causes plastic items to travel both towards the downstream and upstream of the river, making it difficult to predict how much plastic is actually flowing towards the sea. The net plastic flux gives an indication on the total plastic flux averaged over tides, hence the amount of plastic that actually flows seaward, without going back landward. However, downstream of the studied river stretch, plastic items get closer to the river mouth and tidal forces become more prevalent. Therefore, the net plastic flux at the interface with the sea is supposed to be lower than our estimation or even landward directed if tidal forces become significantly stronger than the river discharge.
Lotcheris et al. (2023) estimated that the median residence time of a floating plastic item in the 40 km long river

stretch, that includes Ho Chi Minh City, is 21 days. This result suggests that tides play a crucial role in keeping plastic litters inside the river system and preventing it from entering the sea.

The tidal phase exhibits a correlation with the horizontal distribution of plastic across the river's cross-section. It is evident that plastic exhibits distinct horizontal distribution patterns during ebb and flood tides.
The subsequent graphs illustrate the cumulative plastic distribution across the river cross-section at the three locations, utilizing the median plastic fluxes values obtained from each bridge transect. It's important to note that the horizontal distribution during flood tide is represented for only one location, as our measurements recorded flood tide at Phu Long Bridge on a single occasion.

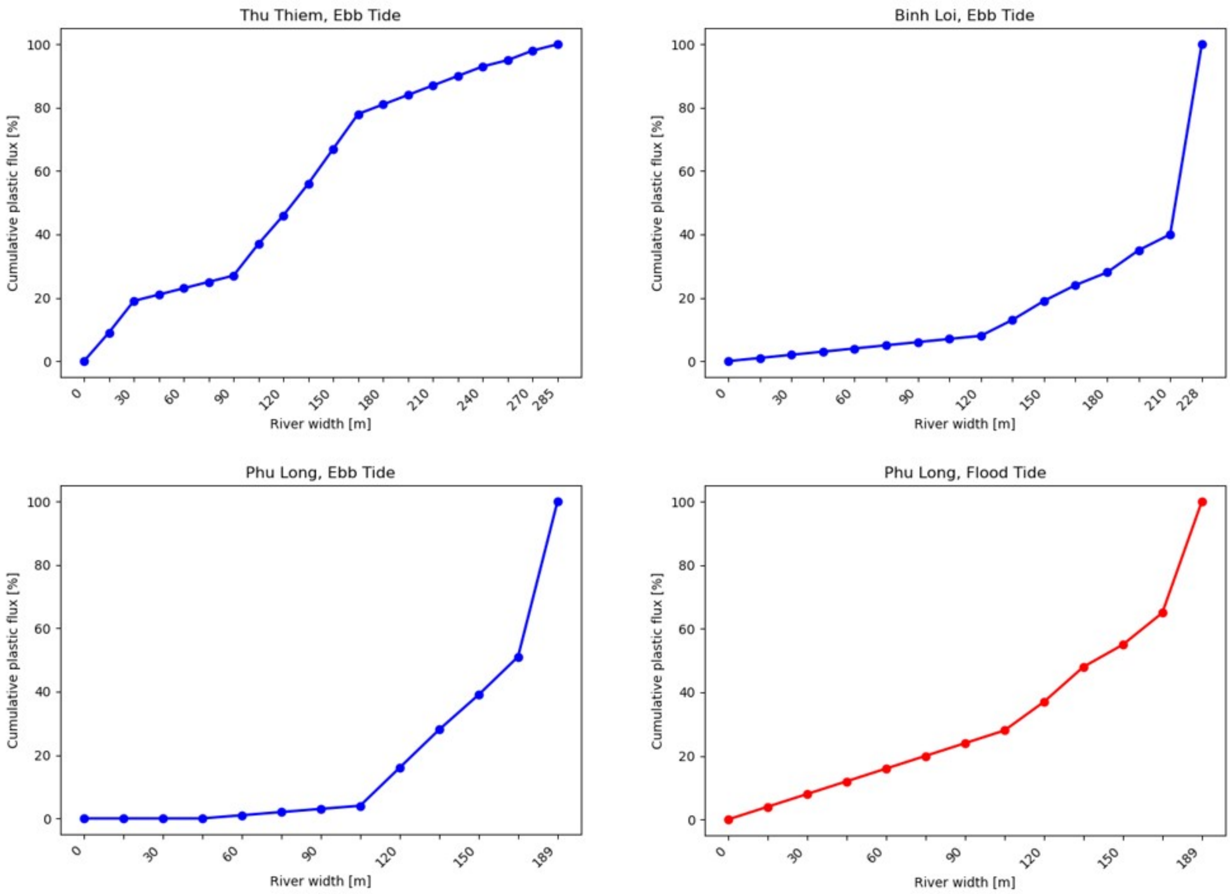


Figure 15:
Horizontal distribution of floating plastic through the river cross section at the three measurement locations in different tidal phases. On the x axis, 0 corresponds to the west bank.

As can be seen by Figure 15, the transport during ebb tide has on average a clear preferential path. In particular, at the downstream reach of our study area (i.e. Thu Thiem Bridge), about 60 % of plastic flows in the central 70 m section of the river. At the upstream and central bridges (respectively at Phu Long and Binh Loi), plastic mainly flows close to the eastern bank of the river. At Phu Long, almost no plastic flux is observed in the first 100 m of the cross section, while more than 40 % of the total litter flows just in the last few eastern meters. The remaining plastic flows between the eastern bank at the center of the river. At Binh Loi, even more plastic flows close to the eastern bank: almost 60 % just in the last 20 m.

We hypothesized that the high sinuosity of the river could be an explanation for the formation of preferential pathways during ebb flow. In fact, secondary circulation patterns originate in curved flow and result in near surface flow directed towards the outer bends of the river meanders and deeper flow directed towards the inner bend. Ultimately, when litter is not dragged down near the outer bend, spiral flow can result in accumulation of litter in the outer bend (Blondel and Buschman (2022)), as further analysed in Section 7.4. In fact, studies by Lotcheris et al. (2023) confirm how floating plastics have a higher probability to interact with water hyacinths in the outer bends of the meanders. If both plastic and water hyacinths are pushed against the outer bend, as we supposed, their coverage density increases and it is more likely that they interact with each other. All the three bridges are located in parts of the river that are preceded by numerous meanders, that could be the cause leading to the formation of these preferential paths.

On the other hand, during flood tide, floating litters flows more uniformly distributed across the river cross section and do not seem to follow specific preferential pathways.

During our measurement campaigns, we could observe one flow reversal event on September, 20 at Phu Long Bridge, transitioning from the flood tidal phase to the ebb tidal phase (High Water Slack: HWS). During HWS, the progression of the free surface water stream decelerated, initially near the riverbanks and subsequently extending to the central region of the river. In the same way, flow reversal started close to the banks and then extended to the whole river cross section.
Figure 16 shows the temporal evolution of the near surface flow velocities during HWS at each transect. We supposed that slack water acts as a proxy for plastic re-distribution over the cross section of the river. In fact, the formation of horizontal velocity gradients in the river cross section during flow reversal, could be responsible for horizontal mixing of floating litter and pick up of plastic accumulated close to the banks.

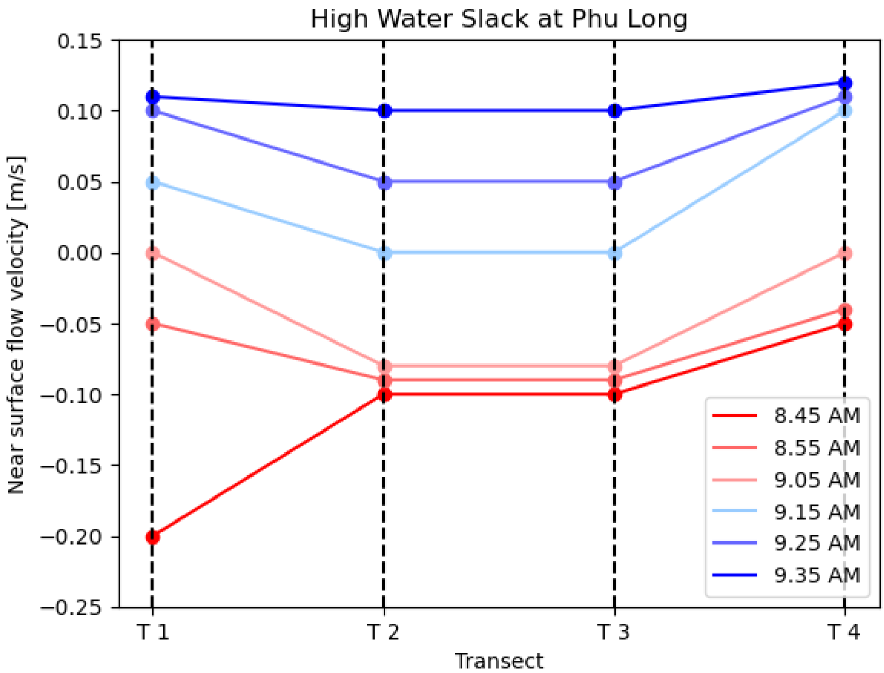


Figure 16:
Evolution of near surface flow velocity during HWS: flow reverses first close to the banks, then in the middle of the cross section. Flood tide is plotted in red, while ebb tide in blue.

Our study did not include a tidal constituents analysis, through which discharge values could be interpolated. We only estimated plastic fluxes at the same time as discharge measurements. Therefore, we relied solely on field measurements of the discharge, coupled with visually counted plastic fluxes, as analysed in Section 7.3. Future studies could include an interpolation of discharge values from tidal constituents for the month of September, to pair with measured plastic fluxes in the field. This could help validating the discharge-plastic flux relation that has been derived below.

7.3 Relation between plastic flux and river discharge

In a tidal system such as the Saigon River, river discharge and plastic transport are highly positively correlated during dry seasons (Schreyers et al. (2023)). In our research, we showed that the correlation is also very strong in the wet season.
In fact, a linear regression function has been derived to explain the correlation between the instantaneous measured discharge and the associated plastic flux. Discharge was measured at different phases of the tide, as

explained in Section 6.4, resulting in both seaward and landward directed flow.

At first, we plotted the whole dataset in a graph pairing measurements of river discharge and plastic flux. For each set of measurements that covers the entire river cross section, the total cross-sectional discharge, determined as in Section 6.2 is paired with the cross sectional plastic flux estimated at the same time. The resulting scatter plot is shown in Figure 17

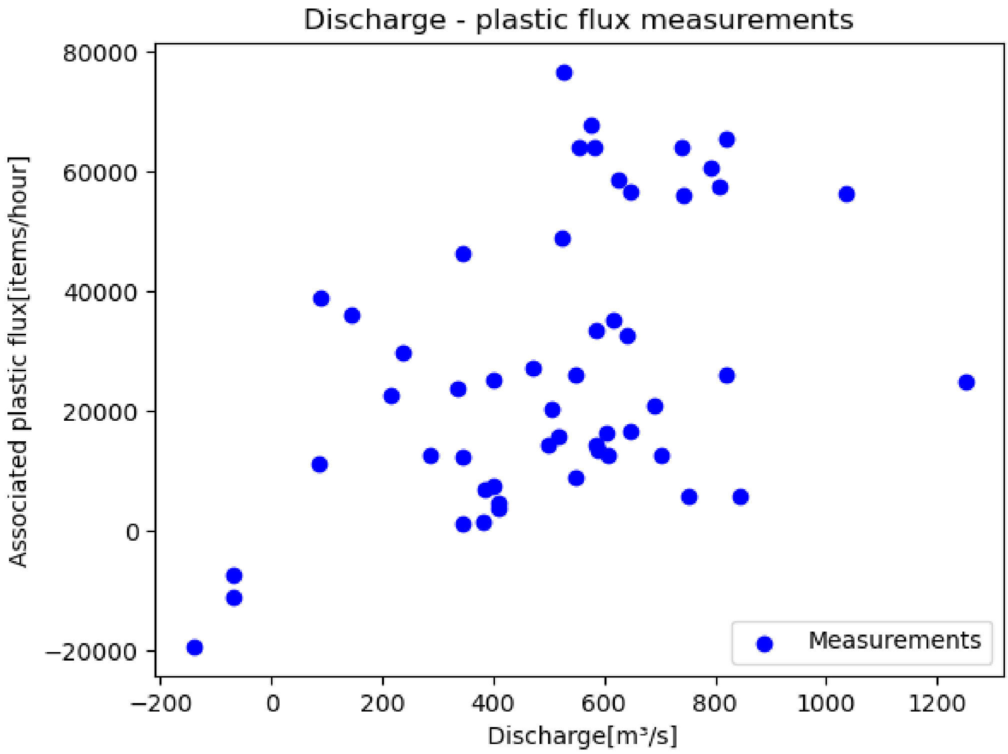


Figure 17:
River discharge and plastic flux considering all the measurements.

Looking at the whole dataset, it is noticeable that the measurements are very scattered and do not follow a well defined trend. We hypothesized that such a big dispersion in data can be addressed mainly to random errors occurred during measurements. These errors included both human-induced ones and errors that can derive from the extrapolations of the data. Indeed, our plastic flux estimates are extrapolated from brief 130-second measurements to values expressed in items per hour. When measuring, we only counted the plastic passing through the observation segment that corresponds with the length of the river transect that the camera can capture. Moreover, we assumed uniform plastic flux across the entire transect based on calculations from the observation segment. Additionally, the visibility of the pictures that are used for plastic flux estimates was highly variable and depended on the weather conditions and on the sun glint, along with the quality of the picture itself, that was not always the same.

To minimize the effect of errors in measurements, and hence reduce the impact of outliers in the observations, the linear regression model was based on daily median values obtained through box plots. For each day of measurements, box plots were generated for each bridge transect, for both discharge and plastic flux estimates. By doing so, we could obtain visual insights on the distribution of data taken at the same point of the bridge, on the same day and during similar external conditions. The median values of discharge and plastic flux at each transect have been then summed to obtain median values of the total cross-sectional plastic flux and river discharge.
Box plots allowed us to visualize the distribution of our data sets, highlighting the median values and identifying possible outliers. Figures 18, 19 and 20 show the big variability of data for both river discharge and plastic flux estimates at each bridge transect during each day of measurements. Discharge values are highly dissimilar within distinct transects because of their varying length and depth. Plastic transport rates also vary

widely between transects because of preferential pathways that floating plastic tends to follow (Section 7.2). Based on the daily median values of discharge and plastic fluxes, more clear tendencies in plastic transport could be identified and a regression line has been drawn, as shown in Figure 21.

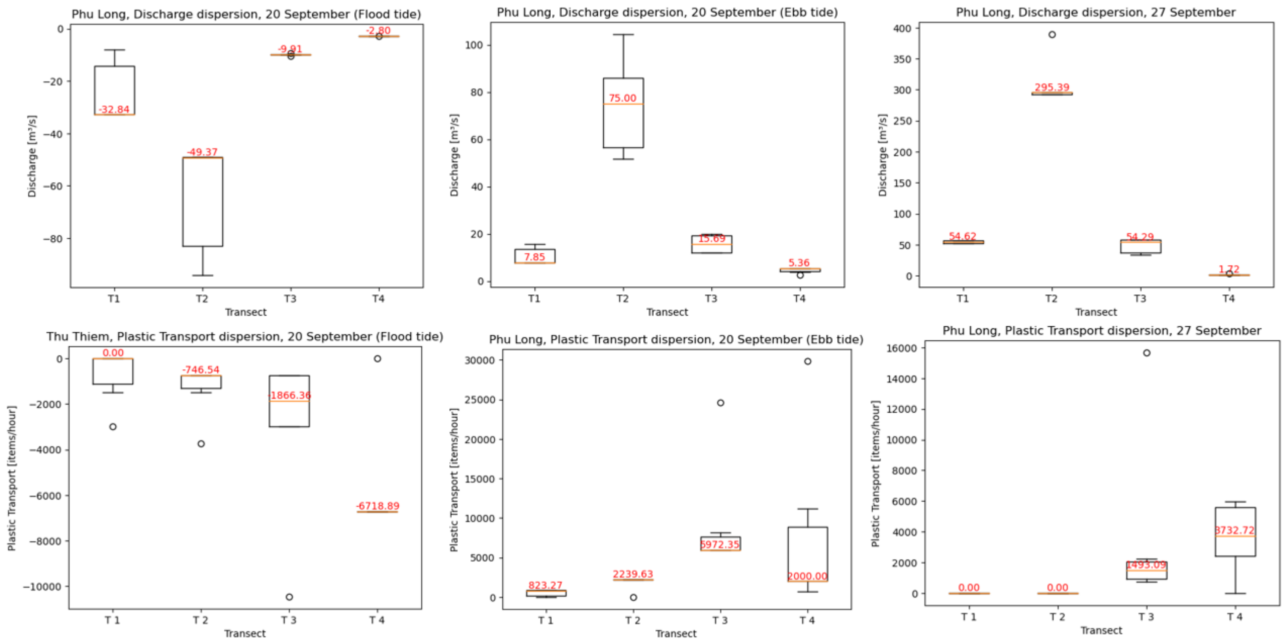


Figure 18:
Data variability at Phu Long Bridge.

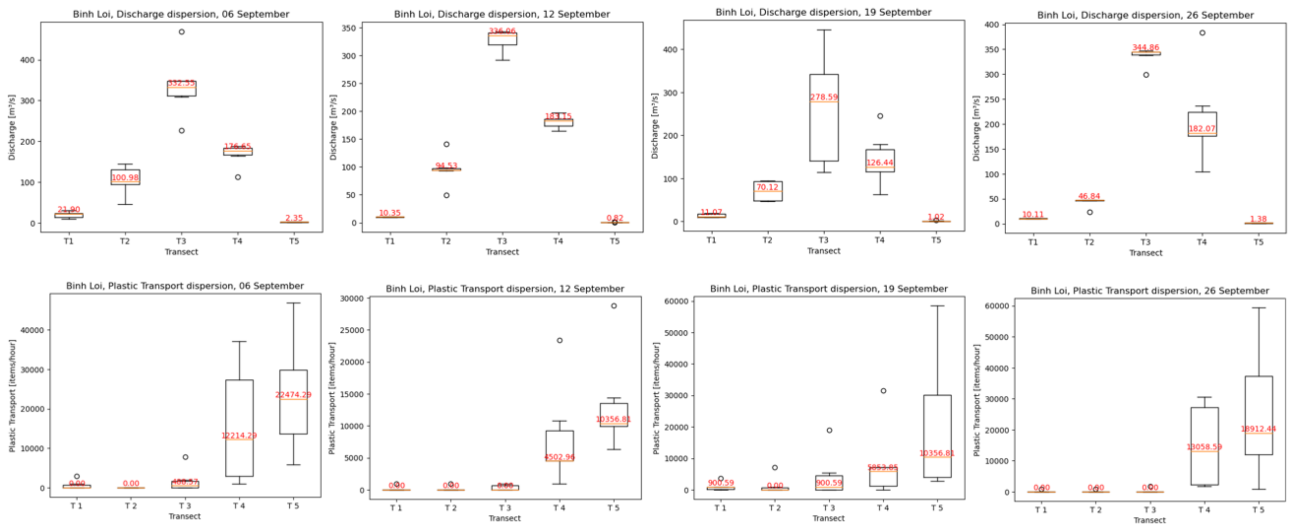


Figure 19:
Data variability at Binh Loi Bridge.

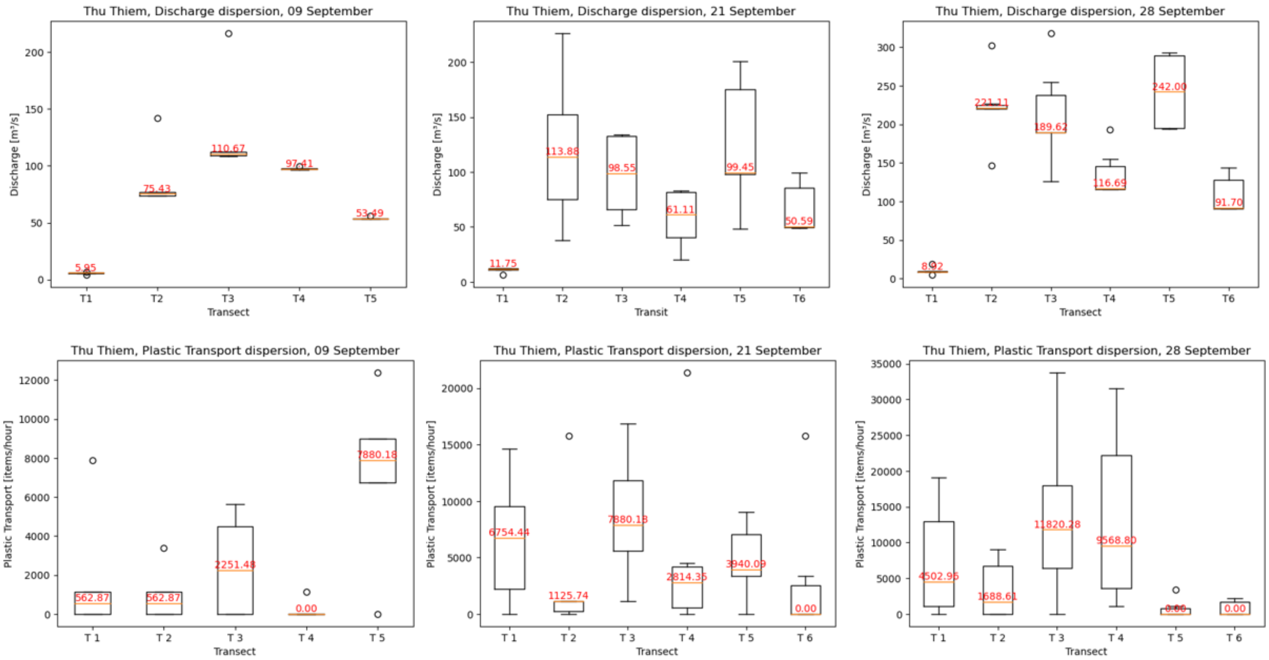


Figure 20:
Data variability at Thu Thiem Bridge.

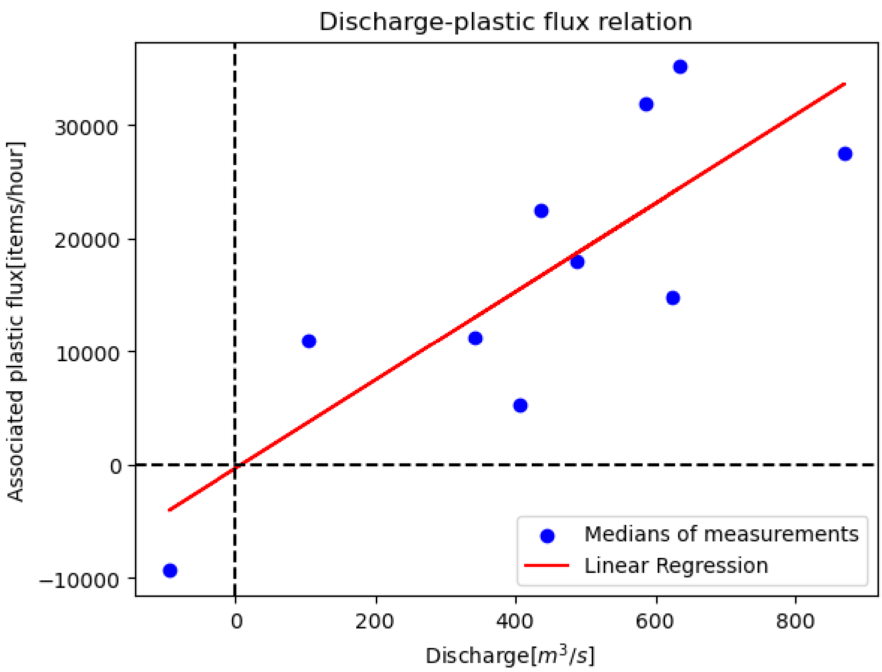


Figure 21:
Relation between median river discharges and median plastic fluxes.

This "clean model" based on median values shows a very strong relation between the river discharge and plastic fluxes (Spearman's rank correlation coefficient: ρ = 0.83, p value = 0.003), in accordance with what previously determined by Schreyers et al. (2023) during more dry months.
The model might suggest how, during the rainy season, the relation between river discharge and the associated plastic flux is stronger than in the dry months. In fact, our estimate predicted the flux to increase with the

discharge by a factor of almost 40:

$$F[\frac{items}{hour}] = 40\frac{items \cdot s}{hour \cdot m^3} \cdot Q - 326\frac{items}{hour} \tag{12}$$

This value is more than 3 times higher than the value estimated for dryer months (Schreyers et al. (2023)). Thus, during the wet season and during intense and continuous rainfall, plastic flux increases with the discharge at a higher rate than in dry periods. We believe that this is a direct consequence of the positive relation between rainfall and water level (Camenen et al. (2021)), as already mentioned in Section 7.1. During the rainy season, the tide-averaged water level is generally higher than during dry periods and a big quantity of plastic items that are normally deposited on the river banks enter the river and are transported with the flow. However, the increase in plastic transport starts with a shift of 2 to 3 months after the beginning of the rainy season. This can be confirmed by looking at data from Van Emmerik et al. (2019), that show an increase of monthly mean plastic outflow from the month of August, hence approximately 3 months after the beginning of the rainy season onward. This results in higher plastic transport in the wet season than in the dry season.

The relation also shows that for similar values of water discharge, a wide range of plastic flux can be expected. For example, with a river discharge of about 600 m^3/s, the plastic flux can vary with a factor of almost 3: ranging from around 15000 *items/hour* to around 35000 *items/hour*. This discrepancy is supposed to be dependent on the varying contributions of different plastic types to the overall plastic transport (Schreyers et al. (2023)), as further discussed in Section 7.7.

For a null discharge, the regression line predicted a negative landward directed plastic flux of -326 *items/hour*. However, the model intercept with the plastic flux axis is not accurate enough since measurements during the flood tide phase could only be obtained for a single day. We suggest to draw a linear regression with more data for both ebb and flood tidal phase and possibly with the same amount of measurements for the two phases to have a better estimate. However, it could be agreeable that for a null water discharge, a non-zero landward or seaward directed plastic flux can be expected, although being very little. Plastic could in fact be locally mobilized by strong winds while the average free-surface flow velocities are null. However, observing a completely null river discharge is not likely since slack water is not a simultaneous process over the depth: in non-uniform unidirectional flow, flow reversal near the seabed occurs before flow reversal near the water surface. Moreover, flow reversal does not happen uniformly across the surface cross section (Section 7.2).

The model was derived considering the measurements from the three bridges altogether. Not enough data was available to draw three distinct models for the three locations. Nevertheless, given the close proximity of the three bridges, it is reasonable to assume that there are no significant factors contributing to variations in the discharge-flux relation across these locations, apart from increases in plastic input associated to higher population density as the river traverses more densely populated areas of the city.

7.4 Plastic concentrations and accumulation zones

The floating plastic flux can be expressed as a function of the free surface flow velocity for a given concentration of plastic in the upper layer of the river, down to the first visible 10 *cm*.

We derived an average concentration of the plastic items in the upper 10 *cm* layer for each river transect at each bridge. In fact, considering a homogeneous floating plastic concentration in the horizontal direction would not be accurate, given the presence of evident preferential pathways that plastic litter follows (Section 7.2). Consequently, a concentration was derived for every day of measurement at every river transect, diving the median plastic flux expressed in $items/(hour \cdot m^2)$ by the median free surface flow velocity in that transect $[m/hour]$. The resulting average concentrations are shown in Table 3, and refer to a 1 m^3 volume that corresponds to a surface area of 10 m^2 extending down to 10 *cm* deep. These concentrations, multiplied by the measured free surface flow velocity, give an estimate of the free surface plastic flux of a given transect per m^2. Adding the transect-specific fluxes together, the total cross sectional plastic flux, expressed in $items/(hour \cdot m^2)$ can be derived. Note that we don't make a distinction between free floating plastic and hyacinth entrapped plastic when describing the flux-density.

Table 3: Flowing plastic average concentrations c [$items/m^3$], and average near-surface flow velocities v_{ns} [m/s]

Phu Long Bridge						Binh Loi Bridge			Thu Thiem Bridge		
Ebb Tide			**Flood Tide**			**Ebb Tide**			**Ebb Tide**		
Transect	**v_{ns}**	**c**	**Transect**	**v_{ns}**	**c**	**Transect**	**v_{ns}**	**c**	**Transect**	**v_{ns}**	**c**
1	0.20	0	1	-0.05	0.04	1	0.13	0.03	1	0.08	0.55
2	0.18	0.15	2	-0.05	0.22	2	0.20	0	2	0.18	0.06
3	0.15	0.37	3	-0.05	0.33	3	0.29	0.02	3	0.18	0.45
4	0.05	1.33	4	-0.05	0.57	4	0.28	0.40	4	0.18	0.25
						5	0.14	1.36	5	0.15	0.19
									6	0.15	0

Field observation campaigns and analysis of UAV images (Unmanned Aerial Vehicle) confirmed that riparian zones of the river, such as river banks and floodplains, serve as accumulation zones, where plastic litter gather mainly entrapped in water hyacinths. Plastic items produced by anthropic activities and mainly transported by runoff amongst others, tend to collect in these areas. Due to the variations in hydrological parameters such as water level, the stagnant zones on the river banks could be inundated and plastic could flow back into the river. Moreover, plastic litter flowing close to the river banks can deposit on the river banks in mild flow conditions.
As a consequence, the averagely higher water level that characterizes the wet season can be responsible for the increased plastic flux observed during the wet season (Camenen et al. (2021)), due to the increased pick-up of stagnant plastic on the river banks.
From our observations, we could also note how during tide reversal, some of the plastic and water hyacinths that were staying still close to the river banks were mobilised again (Section 7.2).

It was not possible to clearly determine the timescale of the formation of accumulation zones, as we do not know how many plastic items that flow close to the river bank are actually stopped and accumulate. However, based on our observation campaigns, we could note how the residence time of items in these stagnant zones is generally low. In fact, each bridge was analyzed once a week, and the accumulation zones highly changed in dimensions and items composition during different observations.

Analysing the variations in plastic quantities and concentrations in stagnant and accumulation zones such as the river banks is crucial to determine how much plastic enters and leaves the river system and as a consequence, how the plastic transport downstream is influenced. In our case, as highlighted in Section 7.6, upstream-located accumulation zones do not diminish the plastic flux moving towards the downstream of the study area. In fact, it is supposed that a big quantity of plastic enters the river system downstream of Phu Long Bridge, where the river flows through the central areas of the city. However, a field trip organized downstream of the study area confirmed that little plastic quantities are found in the Can Gio Mangrove Forest, close to the river mouth. This suggests that accumulation zones, together with the effect of tides opposing the direction of river discharge, are responsible for retaining a lot of plastic and preventing it from flowing towards the sea. Lotcheris et al. (2023) estimated the retention time of a floating plastic items in the 40 km- long stretch of the Saigon River that flows across Ho Chi Minh City to be on average 21 days.

To measure plastic densities in accumulation and stagnant zones, we relied on a python code developed by Schreyers et al. (2023), that could classify plastic items and hyacinth patches as a function of their color. A surface area of 10 m^2 was considered. By doing so, plastic items could be counted in a total accumulation volume of 1 m^3, down to a depth of approximately 10 cm, corresponding to the visible depth. This is consistent with the volume considered for flowing plastic concentrations. Plastic concentrations were measured selecting UAV images in which a big quantity of hyacinth patches were visible close to the river banks. In fact in accumulation zones, plastic items and water hyacinths tend to accumulate together, as confirmed by our visual observations. The estimated average concentration of accumulated plastic in these areas was 57 $items/m^3$.

The accumulation zones we identified are situated in close proximity to the riverbanks. Additionally, the UAV images we utilized emphasized that these accumulation zones were predominantly concentrated in the

upstream study area and on the eastern bank. In fact, we believe that secondary circulation patterns result in spiral flow that can lead to accumulation of litter in the outer bend of meanders, as already mentioned in Section 7.2 and highlighted by Blondel and Buschman (2022). Therefore, we compared the plastic concentration found in accumulation zones with the concentration of flowing plastics in the easternmost transect of Phu Long Bridge (the upstream bridge). The accumulation zones exhibited a concentration that was 43 times higher.
This result suggests that a big part of the plastic that flows in the upstream reach close to the eastern river bank accumulates in accumulation zones. However, after increases in water level and flow velocity, stagnant plastic can be re-entrained. We believe that these processes do not only occur in the studied stretch, but also further downstream, ultimately reducing plastic fluxes towards the sea.

Note that we do not make a clear distinction between accumulation and stagnant zones, since they both form in riparian zones of the river and are difficult to distinguish. The concentration of these areas was calculated only considering wet items, and not dry plastic on top of river banks. Moreover, the UAV images that we used to this purpose were taken on one single day of July. We suggest that more images should be analysed to obtain more reliable estimates. Additionally, further research should be taken to better understand the residence time of plastic litter inside accumulation and stagnant zones, possibly drawing a distinction between the two. This would help quantifying how much plastic is retained and prevented from flowing downstream towards the sea. Finally, we only focused on accumulation areas defined close to riparian zones. However, plastic could also accumulate close to river structures such as bridge piers. Future studies should also address this aspect.

7.5 Influence of water hyacinths in capturing floating plastic

As previously documented in existing studies (Schreyers et al. (2021)), the presence of riverine vegetation, particularly water hyacinths, exerts a significant influence on the movement of macroplastics. Our study confirms how floating plastic transport mainly follows the same pattern as riverine vegetation. Water hyacinth clusters, which can span several meters and become entangled together, possess the capability to capture floating litter. In this section, we present the findings derived from a four-week measurement campaign conducted during the wet season in the month of September, taking into account that one of the scopes of our research is to determine whether water hyacinths can serve as a potential proxy for plastic debris capture.

Water hyacinths play a significant role in the study due to their high diffusion in the Saigon River. The patches are so extensive that they can be monitored through remote sensing platforms like Sentinel-2. To gauge the extent of riverine vegetation impact, the study by Janssens et al. (2022) focused on detecting hyacinth coverage in the Saigon River. The results of this study revealed that plant coverage varied significantly, ranging within four orders of magnitude over the entire study period. This coverage ranged from $2 \cdot 10^{-2}$ to $2 \cdot 10^{2}$ *hectares*, equivalent to 0 % – 14 % of the entire study area, which encompassed 1.26 *hectares*.

The paper by Schreyers et al. (2021), investigates the same study area analysed in our project using similar methodologies. However, several distinctions exist between past studies and our research. Schreyers et al. (2021) campaign was conducted in different months of the year, from April to June, while our campaign spanned over a 4-week period during the month of September. Additionally, the former employed two distinct methods for quantifying plastic litter: a combination of UAV surveys and visual counting.
The primary differentiator bewteen their results and our results is the quantity of data gathered and the timing of the campaign which in the past occurred during the dry season, in contrast to our wet season study.
The research from Schreyers et al. (2021) revealed that, on average, 78% of plastic items were entrapped within water hyacinths over the 6-week campaign. In contrast, our four-week measurement campaign estimated that these free-floating plants transported 55% of the total observed macroplastic.
The reason behind these strong difference has to be researched in the seasonality of water hyacinths coverage. The study by Janssens et al. (2022) identifies a clear seasonal cycle in hyacinth coverage, with the highest abundance during the dry season, peaking in February. In contrast, during the wet season, the area covered by hyacinths decreases, starting to increase again from December onwards as can be observed in Figure 22.
The decrease in water hyacinths coverage during the wet season can be explained by the fact that strong rainfall and increased flow velocities may determine higher disintegration rates of the water hyacinth patches. On the other hand, conditions typical of the dry season, such as higher water stability and higher concentrations of nutrients, lead to water hyacinth blooms Janssens et al. (2022).

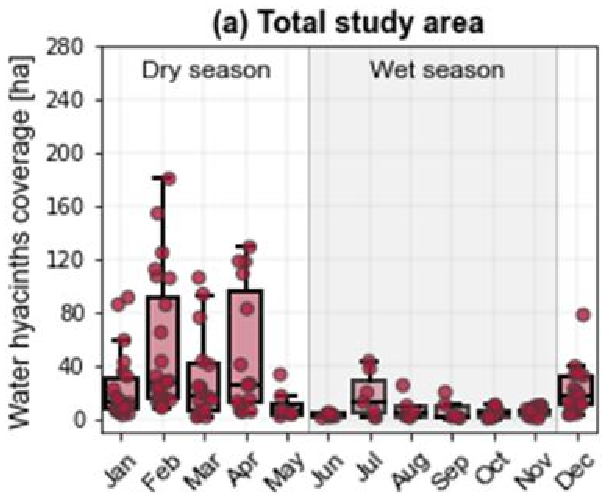
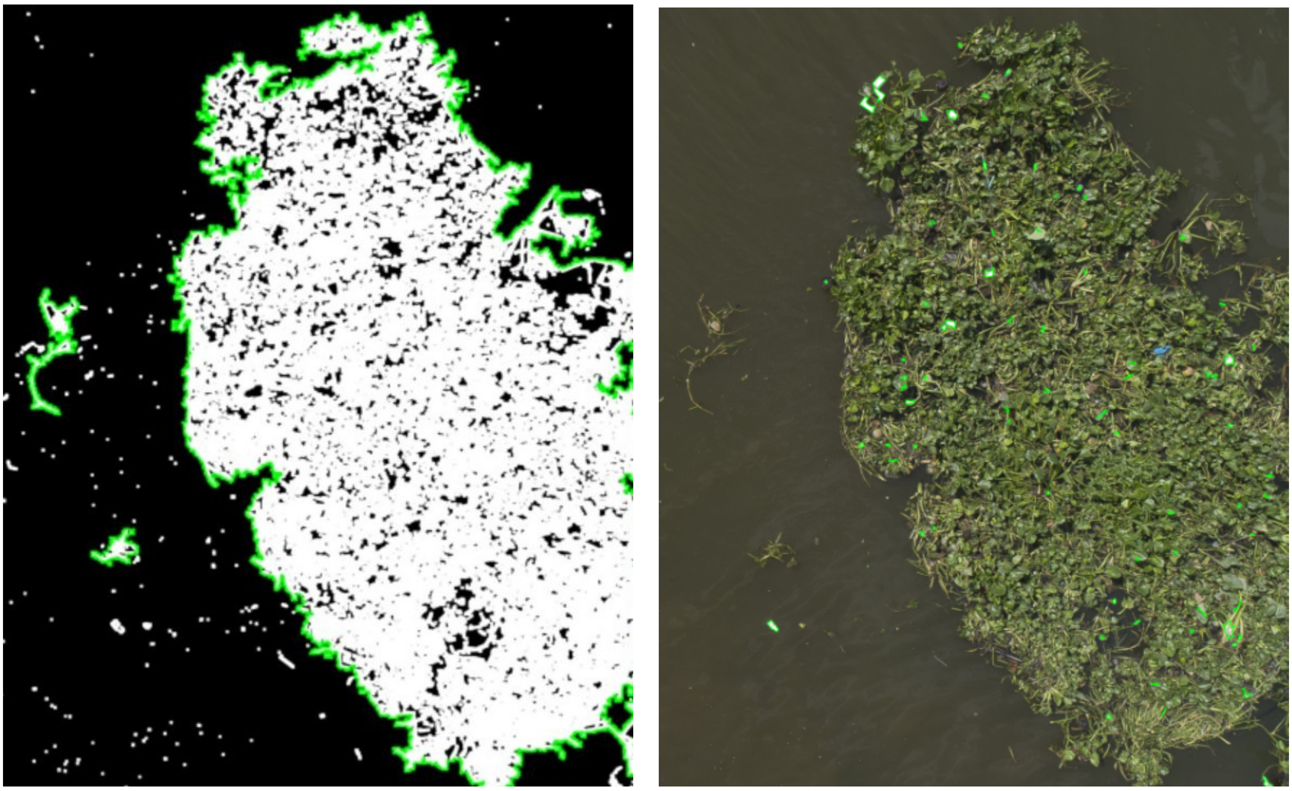


Figure 22:
Water hyacinths coverage changes depending on the dry or wet season (Janssens et al. (2022)).

Water hyacinths are associated with several drawbacks. These plants are notorious for diminishing river productivity by obstructing light penetration into the water. Consequently, this leads to alterations in river flora and fauna, resulting in reduced fish production and promoting eutrophication processes that have adverse effects on water quality (Gupta and Yadav (2020)). Despite the invasive nature of water hyacinths, as mentioned above, they can be seen as valuable tools for capturing plastic litter. For these reasons removal of water hyacinths from rivers serves a dual purpose: mitigating the issues associated with the proliferation of water hyacinths and cleansing the river from plastic litter.

To gain a better understanding on the distribution of water hyacinths and plastic items, we have extended our analysis beyond the initial results derived from the visual counting campaign conducted in September 2023. To do so, we relied on imagery obtained through an UAV survey conducted on July 1, 2023, by our local collaborator, Mr. Le Thanh Khiet Bui, a researcher affiliated with the Institute for Circular Economy Development at Vietnam National University. Due to the unavailability of a drone for our research in September, images collected in the month of July were used. We reasoned that since July falls within the wet season, the UAV images captured on July 1, 2023, would still provide a reasonably accurate representation of the spatial distribution of plastic debris and water hyacinths during this season.
The survey encompassed both upstream (10.51148, 106.42566) and downstream (10.46158, 106.45111) regions of the Saigon River section crossing Ho Chi Minh City. Each flight entailed two overpasses across the river, yielding between 33 to 69 images per flight. These UAV surveys were consistently conducted at an elevation of approximately 10 meters above the water surface. Subsequently, we selected images that contained either plastic items or water hyacinths for our analysis.
To investigate the spatial distribution of plastic debris and vegetation captured during the UAV surveys on July 1, we employed a Python code developed by Schreyers et al. (2023). This code utilized a color filtering approach to identify water hyacinth patches and plastic particles and subsequently calculated their respective areas.
The specific procedures employed by the Python code are outlined in the Appendix 12.2.

It is crucial to acknowledge the limits associated with this approach. First, as previously mentioned, the images at our disposal were from July, while our field measurements were conducted in September. Furthermore, the UAV survey for July was a one-day event, resulting in a relatively limited number of images. Additionally, due to specific image characteristics, such as the presence of shadows, the Python code was occasionally unable to detect hyacinth patches or plastic litter. In such instances, we opted to exclude these particular images from our analysis.
An example of the images obtained through this process can be observed in Figure 23.



(a) Detection of patch contours. **(b)** Detection of item contours.

Figure 23:
Example of processed UAV image [from 1 July 2023] showing the identification of hyacinth patches and plastic litter using the Python code developed by Schreyers et al. (2023).

In the course of conducting UAV flights, both upstream and downstream of the Saigon River section that traverses Ho Chi Minh City, we made significant observations regarding the concentration of materials, including both vegetation and plastic litter, in close proximity to the banks of the river.
The spatial distribution of plastic litter and water hyacinths demonstrates a degree of heterogeneity, aligning with the findings outlined in Section 7.2. Specifically, our analysis revealed that approximately 35% and 26% of the total detected water hyacinth patches aggregate along the eastern bank, both upstream and downstream, respectively. In parallel, when considering the detected macroplastic litter entrapped within water hyacinths, 58% and 34% of the total plastic entrapped can be found at the eastern riverbank, again distinguishing between upstream and downstream regions.
It is necessary to note that the formation of these zones is influenced by several factors, as elucidated in Section 7.2.

Our findings, as depicted in Figure 24, reveal a positive correlation between the distribution of macroplastics and the presence of water hyacinths. The Pearson's correlation coefficient (r) was determined to be 0.59 for the macroplastic area. This result is in consonance with the study conducted by Schreyers et al. (2021) in which a Pearson's correlation coefficient of 0.65 was established. A correlation of 0.59 signifies a moderate positive association between the two variables, implying that as the estimated floating vegetation area increases, the number of plastic items per square meter of vegetation similarly may tend to increase.

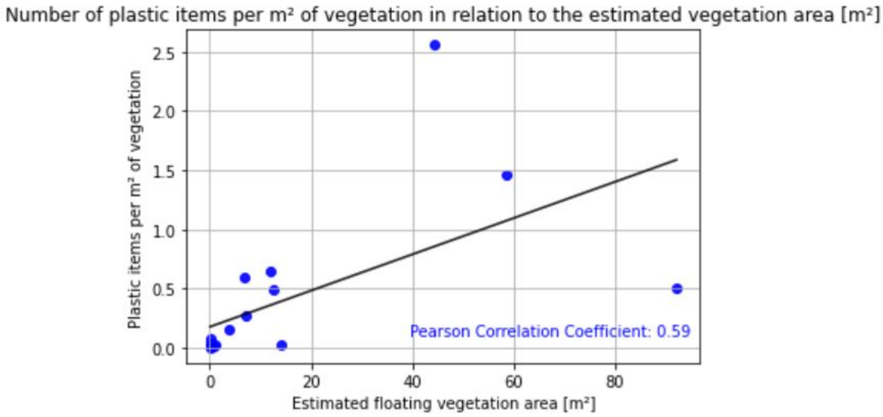
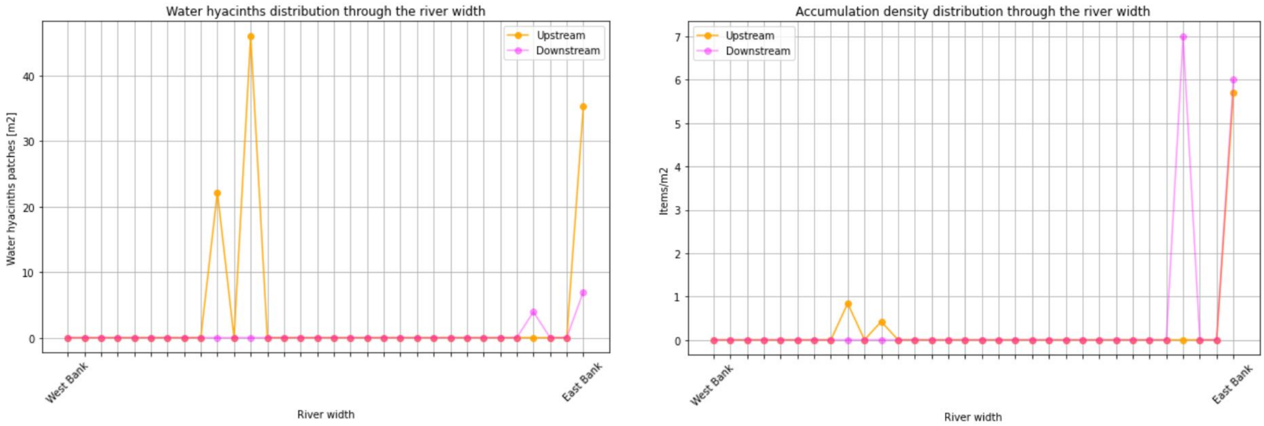


Figure 24:
Plastic accumulation within hyacinth patches: number of plastic items per m^2 of vegetation in relation to the estimated vegetation area in m^2.

Taking into account the entire width of the river, we estimated that on the first of July 2023, the "snapshot" plastic ratio entrapped in hyacinths was 72%. It is essential to recognize that this specific estimate cannot be directly compared to the percentage of total plastic entrapped in water hyacinths that was calculated over a span of four weeks across three different bridges and that is equal to 55% as previously shown.

Using the python code by Schreyers et al. (2023) we were also able to detect the capturing capacity of the water hyacinths: the plastic items entrapped inside the hyacinths were counted and then divided by the area [m^2] of the plants' patches.
The capturing capacity is marked by considerable variability, ranging from 0 items per square meter to 216 $items/m^2$, equivalent to 24 plastic items counted over an area of water hyacinths measuring $1.11 \cdot 10^1$ m^2. The average capturing capacity was estimated to be 29 $items/m^2$.

Figure 25, analyses a "snapshot", obtained over just one day (1st of July, 2023), of the relationship between the spatial distribution of water hyacinths across the river's width [m^2] and the capturing capacity of water hyacinths [$items/m^2$].
Firstly, Figure 25a reiterates the pronounced presence of water hyacinths and the entrapment of plastic along the eastern riverbanks giving interesting results mainly for the upstream segment (yellow trend) of the study area where hyacinths reach a covering area of 35 m^2.
Secondly, comparing 25a and 25b, we could define the trend, already underlined by Schreyers et al. (2021), by which smaller vegetation patches tend to exhibit heightened densities of plastic accumulation, while larger patches show a propensity to accumulate comparatively less litter.
Extended monitoring campaigns are necessary to provide further insights into the spatial interplay between hyacinths and plastics, as well as a deeper understanding of entrapment mechanisms.



(a) Spatial distribution of water hyacinths across the river's width [m^2].

(b) Density of plastic litter accumulation within water hyacinths [$items/m^2$].

Figure 25:
Comparison between the spatial distribution of water hyacinths across the river's width [m^2] and the correspondent density of plastic litter accumulation within the hyacinths [$items/m^2$].

7.6 Plastic flux through the study area

Table 2 illustrates the plastic flux measured in items per hour during the four-week data collection period. To gain a deeper insight into the variation in plastic fluxes from the Phu Long Bridge upstream to the Thu Thiem Bridge downstream, we computed average values of the total plastic flux for each bridge. This revealed that the concentration of plastic litter is twice as high in the downstream area, as depicted in Figure 26. This discrepancy suggests that plastic waste infiltrates the Saigon River between the sampling locations.
The increase in urban density compared to suburban areas correlates with a corresponding rise in plastic pollution. This observed phenomenon is in line with the significant disparities in plastic litter concentrations between the city's northern suburbs and the city center. As illustrated in Figure 2, the higher infrastructure density in the city center results in a more concentrated population and a greater number of shops and restaurants. Consequently, this leads to increased quantities of produced plastic litter.

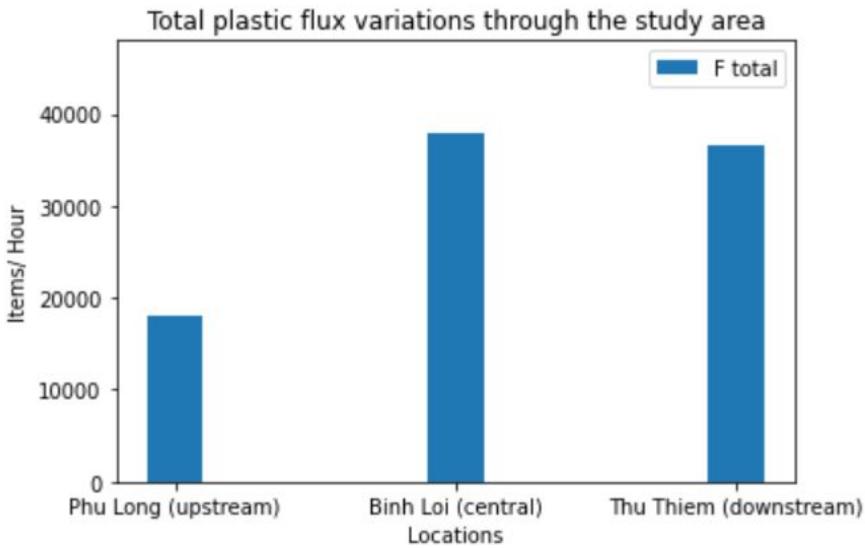


Figure 26:
Total plastic flux changes from upstream to downstream of the considered study area.

During the visual observation phase, particularly in the plastic item counting stage, we classified plastic waste as free-floating or entrapped, as detailed in Section 6.3. The results of this classification are presented in the table below:

Table 4: Free floating and entrapped plastic fluxes: average values

Date	Location	Free floating [*items*/*hour*]	Entrapped [*items*/*hour*]
06/09	Binh Loi	14331	27630
09/09	Thu Thiem	12383	844
12/09	Binh Loi	11708	10357
19/09	Binh Loi	10657	24616
20/09	Phu Long	-4230	-8461
20/09	Phu Long	6221	22396
21/09	Thu Thiem	27393	6567
26/09	Binh Loi	14259	28669
27/09	Phu Long	1244	6097
28/09	Thu Thiem	25142	14072

Similar to our approach with the total plastic flux, we computed average values specific to each bridge for both free-floating and entrapped plastic items. A comparison of the total plastic flux, total free-floating plastic flux, and total entrapped plastic flux is displayed in Figure 27. Notably, the fluctuations of plastic waste traversing the study area vary depending on whether it is free-floating or entrapped.

For both the free-floating plastic flux and the total flux, the plastic waste upstream is of one order of magnitude lower compared to the downstream; notably, the key distinction lies in the manner in which these quantities evolve as we move from upstream to downstream. The increase in free-floating plastic flux shows a linear progression. On the other hand, the total plastic flux demonstrates a slightly different behavior: it exhibits a temporary surge, peaking at a level slightly higher in the midstream area than it does upstream.

Of particular interest are the green bars, indicative of plastic litter entrapped in water hyacinths, which exhibit a peak in items per hour in the midstream zone (Binh Loi Bridge). Surprisingly, this flux is slightly lower downstream compared to upstream, in contrast to the behavior of the total plastic flux and free-floating plastic flow. The reason why the entrapped plastic quantities are lower downstream compared to upstream were already presented in Section 7.5 and has to be researched in the fact that the presence of hyacinths patches is one order of magnitude higher upstream compared to downstream; this leads to a substantial accumulation of entrapped plastic items between the Phu Long Bridge and Binh Loi Bridge segments, where concentrations peak.

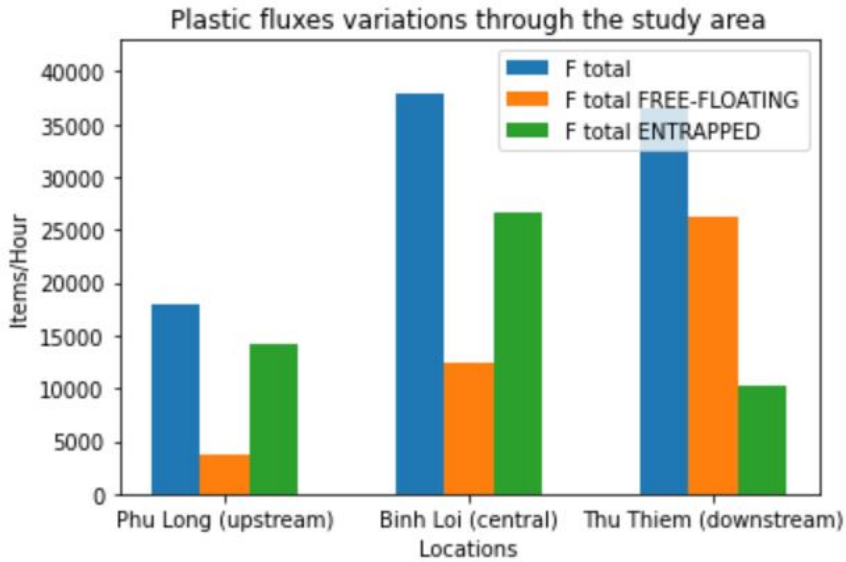


Figure 27:
Total, entrapped and free-floating plastic flux changes from upstream to downstream of the considered study area.

It is important to note that even though canals are not the primary focus of our study, the 30-km canals system present in Ho Chi Minh City (Vietnamplus (2023)) significantly influences the distribution of plastic waste both upstream and downstream of the city. Canals serve as gathering points for macroplastics, facilitating their removal. They function as both entry and exit routes for plastic pollution. In the former capacity, canals, like the main river, provide a conduit for discarding plastic waste into the water system. In the latter role, canals make it easier to collect plastic waste considering that they are man-made waterways with a more controlled and static path, supported by international organisations in the construction of facilities related to drainage, flood control and pollutants removal (Kieu Le et al. (2016)).
Several ongoing projects, such as the Sai Gon Xanh Team and the HCMC Water Environment Improvement Project, address this aspect by organizing garbage collection through small boats, effectively cleaning Ho Chi Minh City's canals from plastic pollution.
In conclusion, while canals may serve as conduits for plastic litter to reach the primary waterway, they also play a crucial role in the localized collection of plastic waste on a smaller scale.

7.7 Plastic categories

Through our study we have identified the predominant types of plastic items present in the Saigon River obtaining the following results: Expanded Polystyrene (e.g.: food containers): 20.35%, Soft Polyolefins (e.g.: plastic bags): 21.95%, PET: 11.66%, Multilayer Plastics (e.g.: food wrappers): 5%, Polystyrene (e.g.: cutlery): 4.16% and Hard Polyolefins (e.g.: bottle caps): 3.39%. Remarkably, the plastic litter encompassed within the "Other plastics" category constitutes a significant portion, amounting to 33.49% of the total items observed within the study area. These items comprise pieces either too damaged to be categorized or not readily distinguishable from the images captured.
Overall our findings align with the results of previous studies on riverine debris (Crosti et al. (2018); Schirinzi et al. (2020); Schreyers et al. (2021)).
In the specific case of our study, conducted in Ho Chi Minh City, Vietnam, the prevalence of items such as food containers and plastic bags can be attributed to the local practice of street food consumption and the widespread use of food packaging for take-out purposes.
While in general, the frequent presence of items such as Expanded Polystyrene (E-PS) can be attributed to the low-density characteristic of this polymer, which enhances its floatability and makes it more susceptible to becoming entangled in water hyacinths.

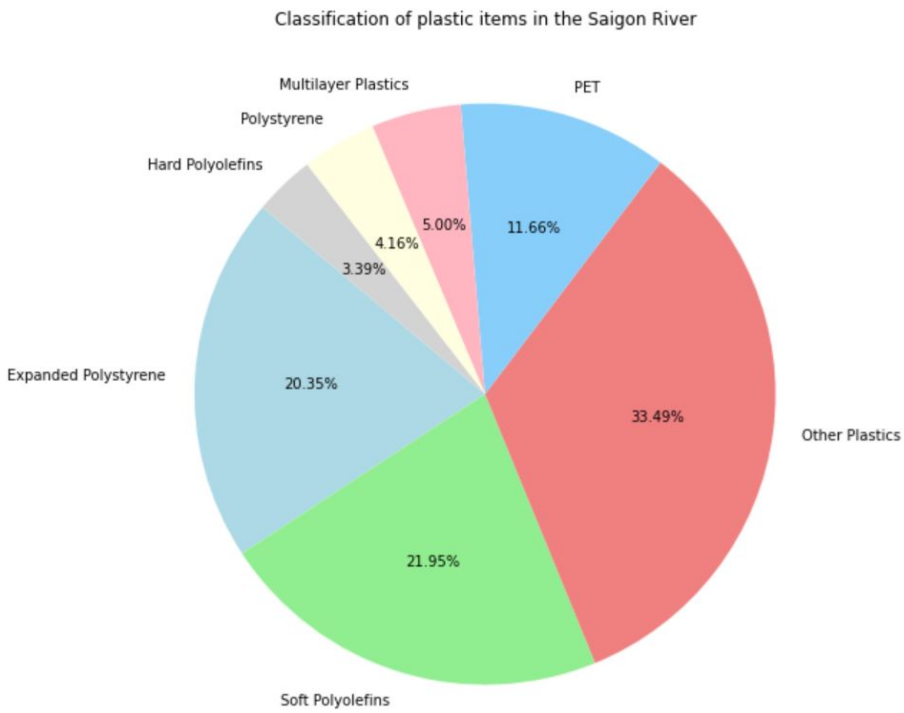


Figure 28:
Classification of the different types of floating plastic items identified in the Saigon River.

The extensive range of sizes, densities, buoyancies, and mass properties exhibited by the various identified plastic categories exert a profound influence on the transport dynamics of plastics. As illustrated in Figure 29, the distinct characteristics of polymers dictate which plastic classes are more likely to freely float and which are predisposed to becoming entrapped within water hyacinths. The graph provides valuable insights into the differential behaviors of plastic categories based on their inherent characteristics. Regarding Polyethylene (PO) soft, Polystyrene (PS), and Polyethylene (PO) hard, it can be observed from the graph that these items are more commonly found as free-floating debris than entrapped within hyacinth patches.
Respectively, 28.39%, 6.54%, and 3.35% are observed as free-floating, while 11.39%, 2.62%, and 2.49% are found within water hyacinths. These results indicate that items like plastic bags are less prone to entanglement.
Multilayer plastics were found in similar concentrations, with 4.63% in free-floating form and 4.84% in entrapped situations. It is worth noting that these results may be influenced by various factors, including potential errors in visual observations and a potential scarcity of multilayer plastics during the measurement period.
Notably, E-PS and PET products exhibit a higher likelihood of becoming entangled in water hyacinths compared to free-floating. Specifically, the free-floating percentages are 11.96% and 8.77%, while the entrapped percentages are 27.23% and 13.87% for E-PS and PET, respectively.
These findings suggest that larger plastic items are more susceptible to be captured by riverine vegetation.
Two explanations for this phenomenon can be identified: the first one posits that larger plastic items become trapped in vegetation patches during their downstream journey due to contact and interference with the vegetation. Conversely, smaller debris items appear to be more mobile on the water's surface and are influenced by water flow. The second explanation suggests that a significant portion of plastic litter enters the river system through vegetation patches often located near riverbanks, where waste is frequently disposed of. Some of these items break down into smaller pieces, disentangle from the hyacinths, and enter the open water. Additionally, the buoyant nature of these items prevents them from easily sinking within the water column (Schreyers et al. (2021)).

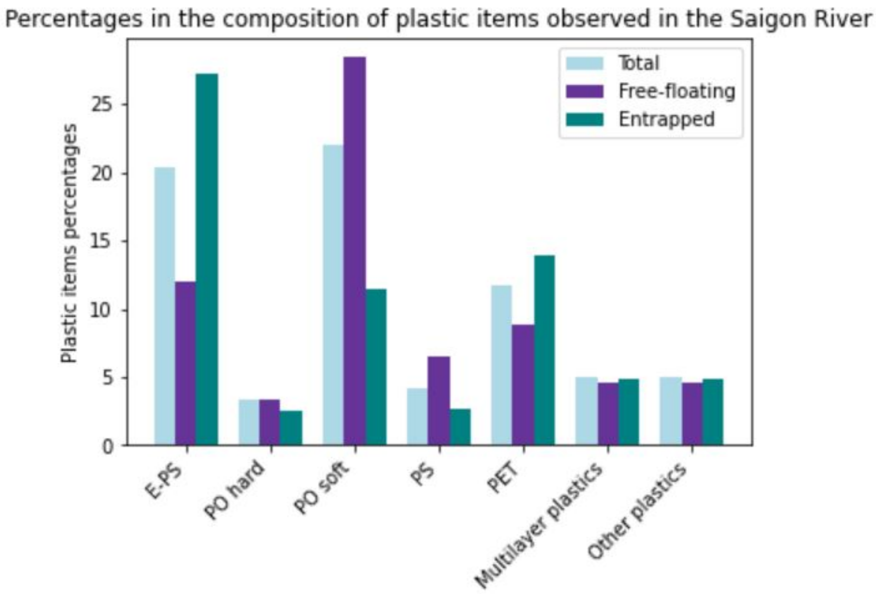


Figure 29:
Percentages in the composition of plastic items observed in the Saigon River: The light blue bars depict the proportions of each individual plastic class in relation to the total plastic count in the Saigon River. Meanwhile, the purple and dark green bars respectively represent the percentages of free-floating and entrapped items within a specific class, calculated relative to the total number of items in that class.

To conclude our examination into the categorization of plastics, we have investigated the variability of net plastic transport based on the specific plastic type.
The net plastic transport rates for each plastic class where defined using the procedure explained in Section 6.4 and applying it to the number of *items*/*hour* computed not for the total plastic but for each single plastic category. The degree of plastic transport fluctuates significantly depending on the category of plastic materials under consideration.
As depicted in Figure 30, a substantial divergence in net transport is evident among various plastic classes, highlighting a remarkable difference of two orders of magnitude. These observations align with the findings of Schreyers et al. (2023) and underscore the significant disparities in plastic transport between different plastic types, ranging from 10^3 *items*/*hour* for E-PS to 10^1 *items*/*hour* for PS. It is important to note that the category labeled "Other plastics" was excluded from our analysis due to its grouping of less easily identifiable plastics.
Our results indicate that the relative contribution of different item types varies significantly, with varying concentrations of plastics at the water surface corresponding to the differing inputs of plastics into the river.

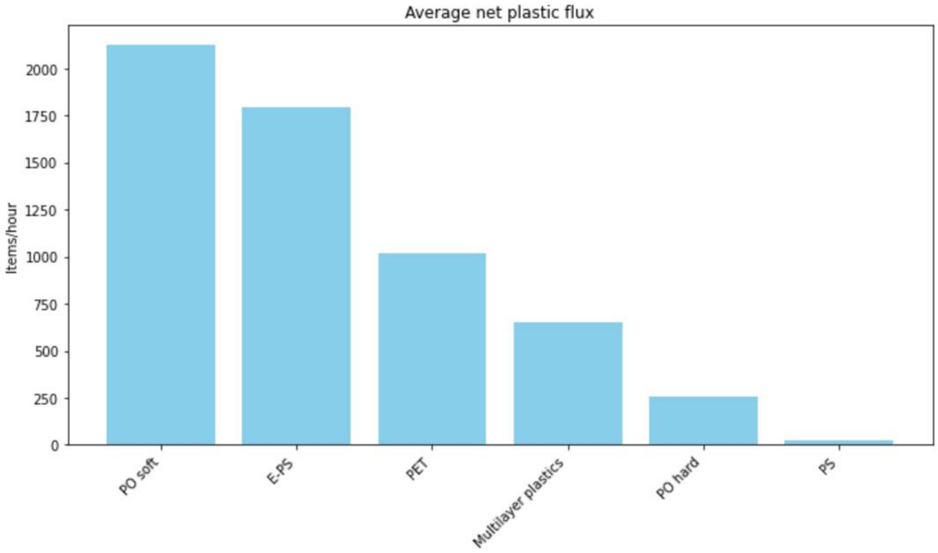


Figure 30:
Net plastic transport rates for each plastic class.

7.8 Secondary influencing factors

In this subsection we list some factors that are belived to play a minor role on plastic transport in the Saigon River.
Firstly, wind was observed to play a role in buoyant plastic transport in the Saigon River. It was common to observe areas of the river surface influenced by strong winds. When free-surface flow velocities were low enough (close to 0.1 m/s), and wind was blowing in the opposite direction, buoyant plastic flux would temporarily stop or even move in the opposite direction for a few minutes. However, the effect of wind opposing the flow direction is not considered to be relevant for plastic transport as its duration and the area involved are generally very low.
Additionally, wind could have a relevant role in mobilizing plastic items that are deposited on the river banks and push them into the river. We consider this as one of the input of plastic in the system, together with runoff and water-level-induced re-suspension.
Another effect that was not looked into in depth was that of ship-induced waves. We suppose that high-speed vessels could induce waves that may have a role in plastic and hyacinth displacement.

7.9 Suspended plastic

Our study is completely focused on floating and visible plastic transport in the river (down to 10 cm below the free-water surface).
Measuring the suspended plastic flows with nets is difficult due to the labour intensity and equipment cost and was not possible in our case. Moreover, methods based on echo sounding to track plastic flows below the water surface show strong limitations (Broere et al. (2021)).
In the case of the Saigon River, studies conducted by Van Emmerik et al. (2019) confirmed that part of the plastic transported in the river sinks and is transported as suspended plastics. This is mainly due to strong turbulence caused by tides, ships, and presence of river structures. However, measurements conducted with multiple- layer nets confirmed that the majority of plastic transported in the upper part of the water column in the Saigon River flows as floating plastic, with about 88 % of plastic flowing in the upper 0.5 m. Therefore, in our case, suspended plastic load is not believed to be a major transport mode. However, relevant volumes of plastic could still flow close to the river bed, but there is no study that addresses this type of transport in the Saigon River. Therefore, a model that only considers visible floating plastic litter down to 10 cm is considered to be enough for a first quantification of the majority of the total plastic fluxes in the river, although it is recommended to further inquire the vertical distribution of plastic fluxes.

8 Conceptual Model

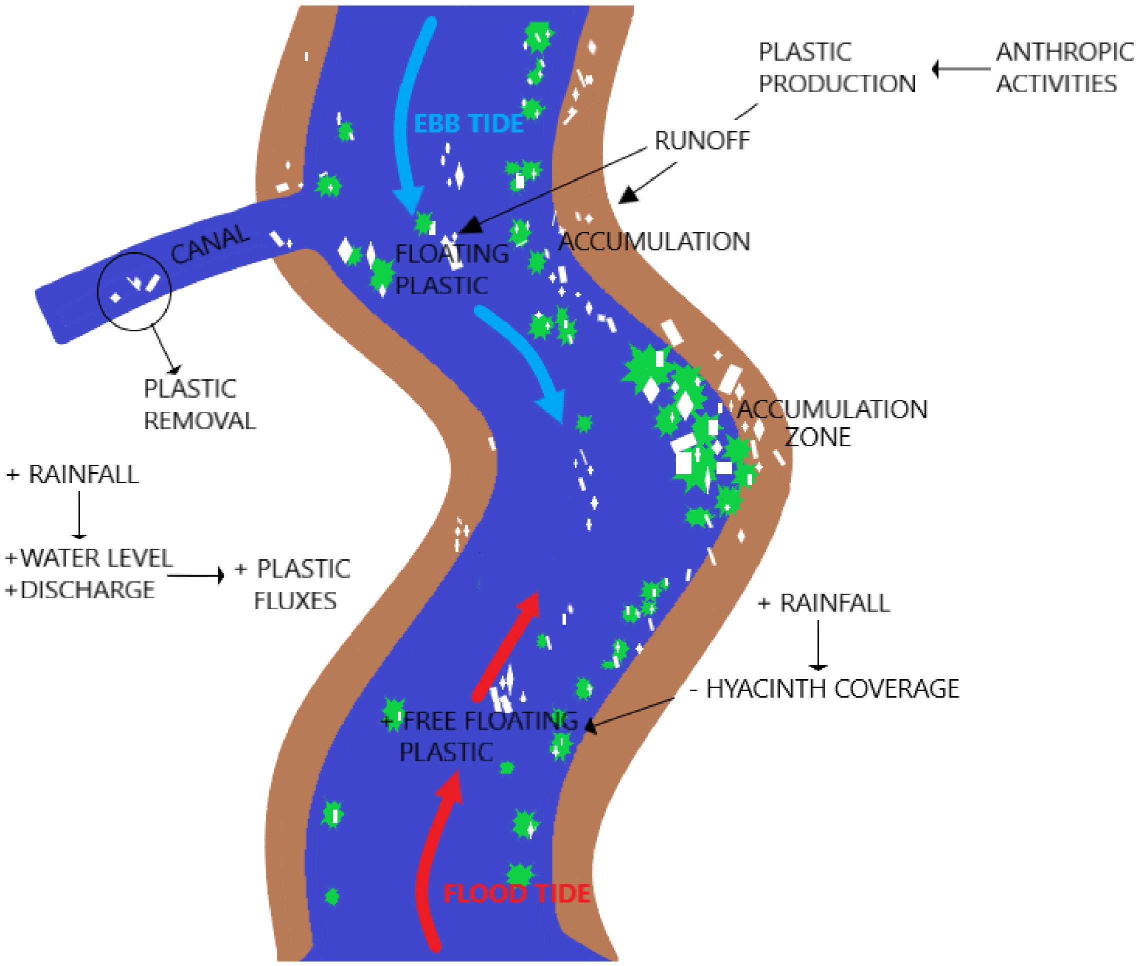


Figure 31:
Conceptual Model on floating plastic transport in the Saigon River.

The objective of this project is to gain a comprehensive understanding of plastic transport within the segment of the Saigon River that traverses Ho Chi Minh City, specifically spanning from Phu Long Bridge to the Thu Thiem Bridge.
In the forthcoming section, we present a summary of various variables that could potentially influence plastic transport. These variables encompassed a range of factors, starting with rainfall and extending to hydraulic elements such as river discharge, tides and secondary flow patterns. We also examined the role of riverine vegetation and the characterization of plastic particles.

A graphic sketch of the model is presented in Figure 31. The model starts with the human element being responsible for plastic production and consumption. Ho Chi Minh City faces a significant challenge due to its inadequate waste collection and management systems, compounded by a lack of environmental awareness and responsibility among the local population. This issue is further exacerbated by the widespread production of single-use plastics. The considerable volume of plastic generated but not properly disposed of in landfills primarily finds its way to the river through natural processes like runoff, wind, and through people throwing waste directly in the river or in the sewage system. These mechanisms result in plastic accumulating along riverbanks or directly entering the water.

Upon entry into the water system, numerous factors influence the transport of plastic. Our analysis has indicated that rainfall, while not exerting a direct impact on plastic fluxes, does have an indirect influence: rainfall

primarily affects the tide-averaged water level and discharge, both of which exhibit seasonal fluctuations in response to rainfall patterns. During the wet season, increased rainfall elevates the mean values of these parameters, resulting in heightened plastic transport. This effect is mainly attributed to the rising water level, which facilitates the remobilization of plastic from the riverbanks.
The model also illustrates the influence of the semi-diurnal tidal cycle, leading to alternating ebb and flood tides that push plastic both seaward and landward. Moving downstream of the study area and closer to the river mouth, the influence of tides become even stronger, resulting in less plastic floating toward the sea.
The quantity of plastics reaching the sea is highly influenced by the presence of accumulation zones, notably riparian zones filled with plastic debris and water hyacinths, mainly located on the river eastern side. Figure 32 provides a zoom on the processes that take place in accumulation zone.

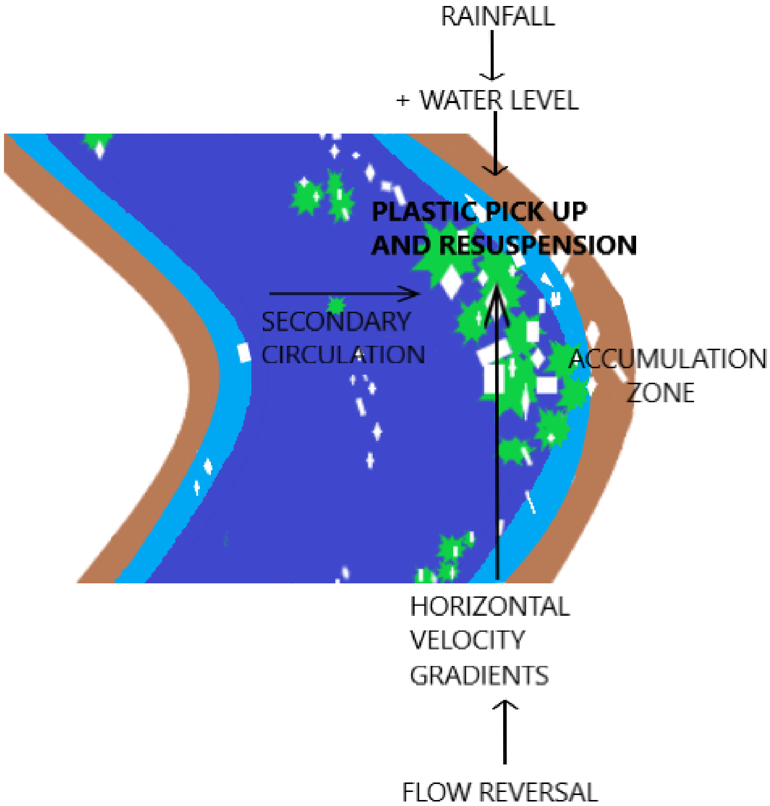


Figure 32:
Main processes that take place in the accumulation zones.

We hypothesised that such mechanisms are not limited to the segment of the river within Ho Chi Minh City but extend throughout the river, ultimately reducing plastic fluxes in the estuary.
The location of these accumulation zones is determined by the creation of preferential pathways followed by plastic items. The river's high sinuosity fosters the development of secondary circulation patterns that drive floating plastic towards the outer bends of the meanders. In this case, this results in substantial quantities of plastic items drifting seaward along the eastern bank. When plastic and water hyacinths come into close proximity to the riverbanks, they can cluster and form accumulation zones. These accumulated items are subject to both deposition, when water level decreases, and remobilization, when water level rises. Furthermore, flood reversal can induce the remobilization of accumulated plastic items near the riverbanks through the formation of horizontal velocity gradients.

Another critical factor in plastic transport is the presence of water hyacinths, which act as a catchment for plastic items, capturing approximately 55% of the observed floating plastic. Notably, this percentage varies between wet and dry seasons due to seasonal changes in water hyacinth coverage. During the dry season, with increased rainfall and flow velocities, the presence of water hyacinths more than doubles, resulting in higher entrapment rates.

Plastic categorization also plays a role, with larger and less dense plastic items, such as Expanded Polystyrene food containers, being more prone to getting entangled in water hyacinths.

The only documented means of plastic removal from the system under our analysis is through man-made canals within the city. In these canals, plastic is occasionally removed by associations and public organisations. However, given the substantial plastic concentrations in the rest of the river, this method appears to be not efficient enough.

9 Potential Solutions

In this section, we will explore solutions that can be carried out by individuals or citizen groups dedicated to contributing to the Saigon River's cleanup. Nowadays, the only method used for removing plastic from the Saigon River involves canals. Associations and public organisations are actively engaged in canal-based plastic removal, easier thanks to the milder flow conditions in these areas compared to the strong currents of the Saigon River. The debris collection in HCMC's canals prior to 2014 was mainly carried out through manual collection. From 2014 on, a machine-based processes have improved waste collection efficiency (Kieu Le et al. (2016)).

As for solid waste management, the handling of floating debris in the city's primary canals is entrusted to public entities like Citenco and the District 8 Public Service Co.. Environmental workers utilise boats equipped with nets on both sides to clean the canals. The collected waste is subsequently transported to the Da Phuoc landfill for disposal, with the extent of sorting depending on the specific public company responsible for the canal area (Kieu Le et al. (2016)). Despite these efforts, a substantial volume of uncollected plastic waste continues to accumulate in the canals, eventually finding its way into the Saigon River; for this reason, it is evident that removal efforts have to be implemented focusing also on the main waterway.

Our research suggests that a practical approach on a smaller scale is to target accumulation areas where large quantities of plastic have been observed. One option is to manually gather plastic deposited along the riparian zones before it can re-enter the water. This strategy may be more effective during the dry season when lower tide-averaged water level results in increased plastic accumulation on the riverbanks.

Another potential solution involves the use of nets to collect hyacinth patches along the riverbanks, which often trap plastic. This approach offers a dual benefit as hyacinths are known for their invasive nature, disrupting river ecosystems and their flora and fauna. Our study indicates that this approach is most effective during the dry season when water hyacinth presence more than doubles, leading to a higher concentration of trapped plastic.

The primary objective of these actions is to have a localized impact on reducing plastic pollution within the river system. However, it is crucial to acknowledge the inadequacies of Ho Chi Minh City waste management system, which lacks essential infrastructure for the separation and management of plastic waste. We recognize that the proposed solutions operate on a smaller scale and that further development is needed. In the absence of larger-scale cleanup initiatives for the river, these approaches continue to play a pivotal role in the ongoing effort to tackle the issue of plastic pollution in the Saigon River.

10 Limitations and Recommendations

In this section, we will address the limitations encountered throughout all the phases of our research, from the field measurements to the data analysis and the literature review.
The main limitation that we have encountered was that the observations collected during the field campaigns were conducted for only a few hours, and not continuously, restricting the ability to capture the full spectrum of plastic pollution dynamics. Furthermore, we scheduled only one measurement per week for each bridge, which posed limitations on our dataset. The limited measured data complicated the process of establishing meaningful distinctions within the study area. It also hindered our ability to correlate and compare the data with the various other analysed variables which were usually available for different timing and locations.
The main method used to obtain data related to plastic items was visual counting. This method is prone to both human and instrumental errors, potentially introducing inaccuracies in the estimated data. Additionally, camera pictures collected to count the plastic items, sometimes suffered from issues like overexposure or blurriness, leading to the possible omission of plastic particles. Moreover, the instrument used for free surface flow velocity proved to have a poor sensitivity to one decimal place. In the case of the Saigon River, the instrument was not accurate enough given the generally low flow velocities which characterise the river. Furthermore, the method used for the estimation of the discharges led to inaccuracies that derive from assuming prismatic sections of the river, hence characterised by uniform depth values, which do not correspond with the reality.

The Python code used for detection of water hyacinth patches and plastic litter areas relied heavily on colour masks, and there's a risk of missing some particles due to variations in colours not recognised by the spectrum defined in the code. Furthermore, the presence of shadows or overexposed areas in the pictures negatively affected the code's efficiency.
It should also be taken into account that the lack of UAV images, with only one campaign conducted on a single day (1st of July 2023), limited the temporal and spatial coverage, making it challenging to provide accurate and comprehensive results, particularly considering that our campaign was made throughout the month of September. We believe that, when it comes to hyacinths coverage, drone pictures taken in July are representative of the wet season but not accurate enough considering that we developed our study for the month of September. The number of UAV campaigns should be definitely implemented to obtain more accurate results.

The absence of a tidal analysis where the main tidal constituents are counted for, inhibits the validation of the discharge-plastic flux relation, which is derived only for the measured river discharge and plastic fluxes. Moreover, the absence of an openly accessible river hydrograph hinders a comprehensive understanding of the variation of water discharge over time. We believe that conducting a tidal analysis and performing continuous measurements covering entire tidal cycles could be a fundamental step to validate our relation.

Another limitation involves concentration estimates in the accumulation zones. To calculate this quantity, the only data that was provided and used was drone images from a single day in July, as previously mentioned. Therefore, the concentration estimates of plastic in riparian zones may not be accurate and should be calculated again by performing other drone campaigns over the accumulation zones in the month of September. Further studies on accumulation zones densities and their formation timescales may provide essential insight on the formation processes of these areas, and their impact on plastic fluxes downstream. We believe that this could be a crucial step in future research to quantify the impact of these areas, which is believed to be extremely relevant in our study.

The rainfall data was affected by uncertainties arising from averaging hourly precipitation intervals obtained from GPM. Although GPM was considered to be sufficiently accurate for our research, possible future investigations into the influences of rainfall on plastic transport might benefit from a new data collection approach. For instance, deploying rain gauges at various locations within the study area could yield more reliable and comprehensive data for further analysis of rainfall effects.

A final big limitation regards the knowledge gap concerning plastics transported below the water surface. Previous studies confirmed that a relevant portion of plastic items are transported below the water surface, mainly as bed load. Future investigations should include measurements that quantify plastic transport that occurs below the surface, although this proves to be very challenging in the context of the Saigon River.

11 Conclusion

The aim of this research was to investigate the intricate dynamics of plastic transport within the stretch of the Saigon River crossing through Ho Chi Minh City. The Vietnamese megalopolis grapples with a significant challenge in effectively managing its solid waste. This issue is further exacerbated by a rapid increase in urbanization, industrialization, ongoing urban developments, and the population growth. This, coupled with inadequate regulations and policies for waste management, has led to a severe problem of plastic pollution in the Saigon River, which ranks fifth amongst the largest contributors of plastic pollution in Vietnam (Lebreton et al. (2017)).
Understanding the factors influencing plastic transport is crucial when formulating possible solutions, both on a local and a broader scale. Following four weeks of field measurements conducted in September, we commenced the data analysis phase. Section 7 extensively analyzed several factors believed to impact plastic fluxes within the Saigon River. Subsequently, the development of a conceptual model allowed us to interconnect these factors and therefore to better explain the dynamics of plastic transport in our study area.

The Saigon River, characterised by a semi-diurnal tidal cycle, is an extremely complex system which showcases an interwoven network of factors influencing plastic transportation. Our study demonstrates that plastic transport is not prescribed by a single variable but instead results from the interplay of diverse elements. While rainfall's direct impact on plastic fluxes may be negligible, its influence on tide-averaged water level and discharge significantly contributes to the transport of plastic items. We noted a clear seasonal pattern in both tide-averaged water level and discharge, with higher mean values of both variables measured during the rainy season. We observed that an increase in water level aids the remobilization of plastic items, whereas a decrease could lead to the deposition of plastic in the riparian zones. Our research also identified a positive correlation between river discharge and plastic fluxes, particularly accentuated during the rainy season, again indicating a seasonal trend in plastic fluxes.

The action of tides pushes the plastic both seaward and landward, thus reducing the amount of plastic transported towards the sea. The amount of plastic litter reaching the sea is also highly influenced by the presence of accumulation zones, which location is determined by the formation of secondary circulation patterns. These accumulation zones act as storage for plastic litter as fluctuations in the water level can lead to both deposition and remobilization.

A significant part of our study investigated the role of riverine vegetation, particularly water hyacinths, which exhibited a capacity for entrapping plastic. Results indicated that during the month of September 2023, 55% of plastic observed in the study area was entrapped within water hyacinths. These entrapment rates increase during the dry season as the presence of water hyacinths is more than double. Understanding the role of water hyacinths in the Saigon River is crucial to plan for future targeted clean ups.

Our conceptual model was also directed at identifying possible small-scale solutions, such as the manual collection of plastic litter from riverbanks and the use of nets, which could contribute to locally mitigate plastic pollution.

The conceptual model proposed within this study investigated how the interplay of different factors affect the transport of plastic in the Saigon River. While serving as a fundamental framework, further research stands as an imperative step in comprehensively evaluating the influence of each variable and in planning targeted solution to address plastic pollution in the Saigon River.

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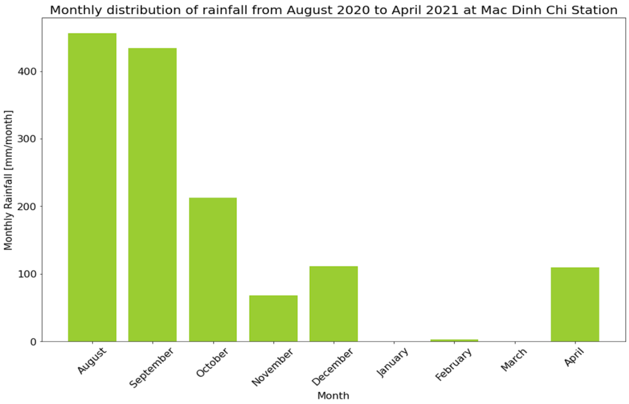
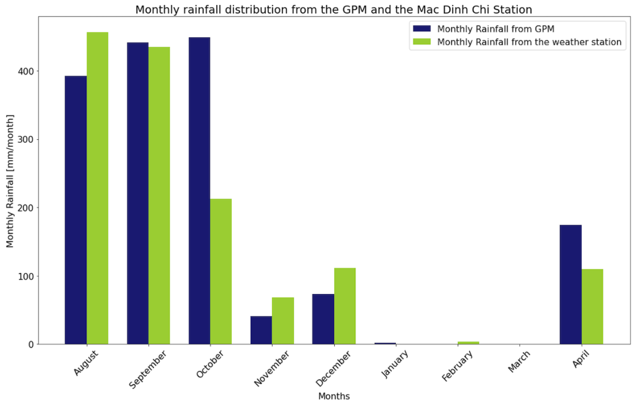
12 Appendix

12.1 Comparison between the rainfall data gathered from GPM and from the Mac Dinh Chi Station

With the newly gathered rainfall data from the Mac Dinh Chi Station, we plotted again the monthly rainfall distribution as displayed in the bar graph in Figure 33.
A seasonal pattern in the rainfall distribution can still be observed, with the months belonging to the wet season accounting for the 84.0 % of the total precipitation for the nine-month period. Considering the already mentioned uncertainty affecting the rainfall data obtained from GPM, the data generally shows similar values except for the month of October, which exhibits a substantial discrepancy. In October, the precipitation records from GPM amounted to 448.75 $mm/month$, whereas the rainfall data recorded at the Mac Dinh Chi Station was 212.4 $mm/month$. The monthly distribution of rainfall differs in the two datasets, with the monthly rainfall values from the Mac Dinh Chi weather station decreasing from August to November, while the monthly values from GPM increase every month in the same period.



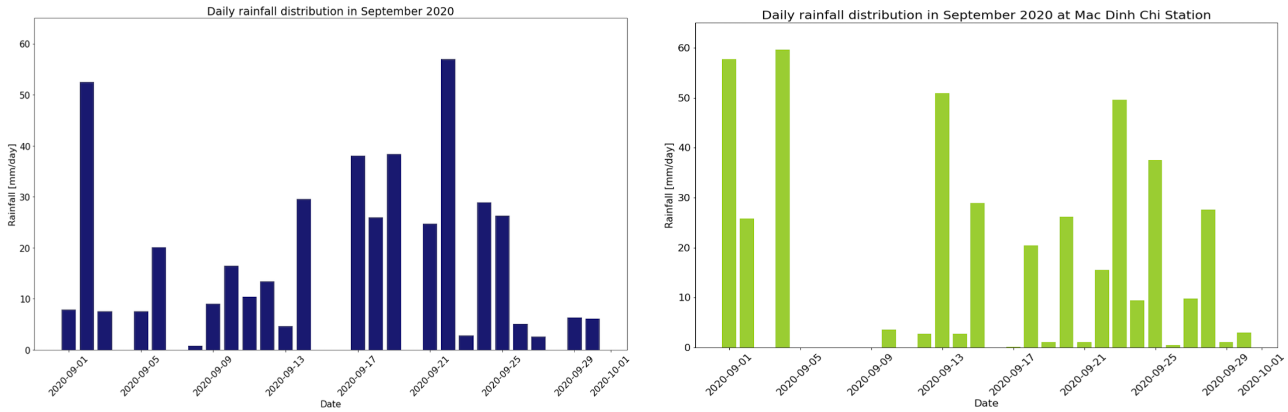
(a) Monthly rainfall distribution from August 2020 to April 2021 from the Mac Dinh Chi Weather Station.



(b) Differences in the rainfall data between GPM and the Mac Dinh Chi Weather Station.

Figure 33:
Comparison between the rainfall data gathered from GPM and the Mac Dinh Chi weather station.

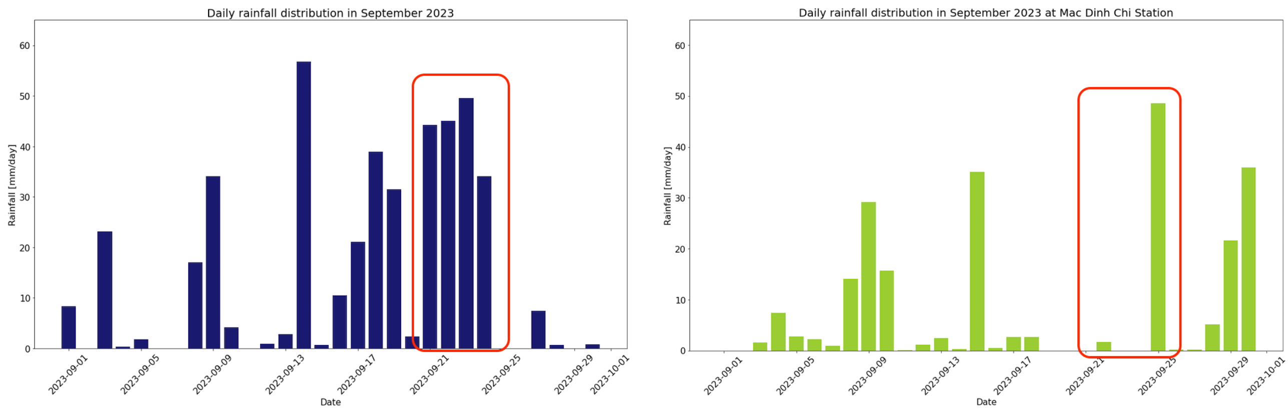
Figure 34 and Figure 35 display the daily rainfall distribution for September 2020 and September 2023 as measured both from GPM and at the Mac Dinh Chi weather station. Comparing these bar graphs reveals significant distinctions.
There is a contrast in the daily values between the two datasets (GPM and Mac Dinh Chi) leading to very different daily distributions from the two datasets. One possible explanation to this discrepancy could be attributed to differences in the timestamps of the rainfall data from the two sources. While the daily rainfall values from GPM were the sum of the hourly values from midnight of that day until midnight of the next day, the Mac Dinh Chi weather station provided daily values from 7:00 am of the day before to 7:00 am of the day considered. However, this does not seem to be the only cause for the different distributions. When looking at the daily rainfall values from GPM of September 2023, it can be noticed that towards the end of the month there were four consecutive days of heavy rain, specifically from September, 21 to September, 24. The same pattern is not observed in the rainfall data from the weather station where only one heavy rainfall day was recorded. This could suggest that the weather station may not consistently provide accurate results.
Moreover, although the monthly rainfall for September 2020 remains relatively consistent with the GPM data, amounting to 407.2 $mm/month$, September 2023 records a notably lower monthly total of 232.5 $mm/month$, in contrast to the 398.7 $mm/month$ recorded in September 2023 by GPM.



(a) Daily distribution of rainfall in September 2020 obtained from GPM.

(b) Daily distribution of rainfall in September 2020 obtained from the Mac Dinh Chi station.

Figure 34:
Comparison between the daily rainfall data gathered from GPM and the Mac Dinh Chi weather station in September 2020.



(a) Daily distribution of rainfall in September 2023 obtained from GPM

(b) Daily distribution of rainfall in September 2023 obtained from the Mac Dinh Chi station

Figure 35:
Comparison between the daily rainfall data gathered from GPM and the Mac Dinh Chi weather station in September 2023.

12.2 Python code to detect the areas of water hyacinths' patches and floating plastic items

The python code developed by Schreyers et al. (2023) was employed to compute the area of the water hyacinths' patches and the area of the floating plastic items. The images used by the Python Code are the pictures of the Saigon River taken during the UAV survey conducted by our local collaborator, Mr. Le Thanh Khiet Bui, upstream and downstream of the section of the river that crosses Ho Chi Minh City. The process followed by the code is explained in Figure 36.

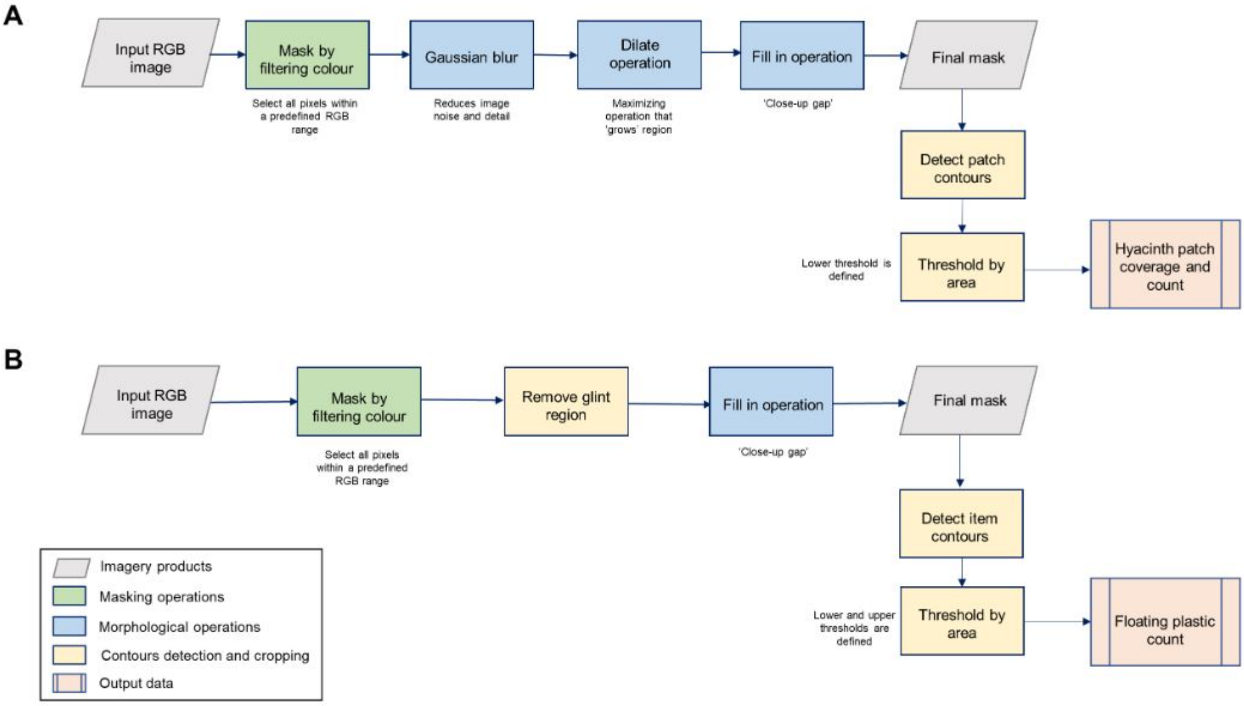
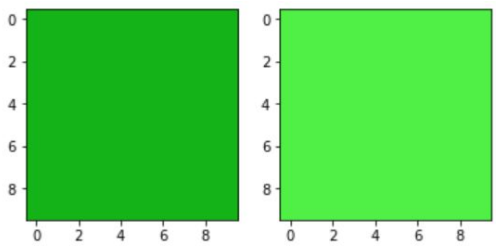
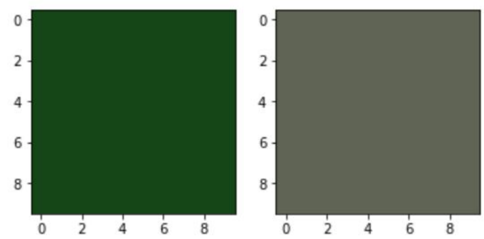


Figure 36:
Processing steps to detect: A. Hyacinth patches and B. Floating plastic items (Schreyers et al. (2023)).

For our analysis we adapted the code to process diverse images using the color masks presented in Figure 37 for the detection of riverine vegetation patches. To detect the floating plastic items from the drone images the code filtered the pictures using white and grey tones as can be observed in Figure 38.



(a) Light green tones.



(b) Dark green tones.

Figure 37:
Color masks for the detection of water hyacinths patches.

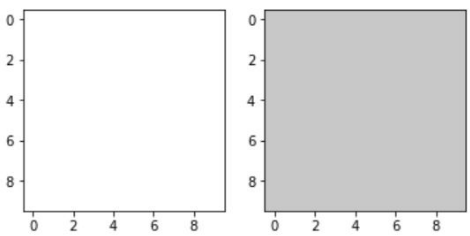


Figure 38:
Color masks for the detection of floating plastic litters.