Plastic Waste Material Flow Analysis for Thailand

SUMMARY REPORT

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ABBREVIATIONS & DEFINITIONS

BMA	Bangkok Metropolitan Administration
DELWAQ	Fate and transport modeling software
D-Emissions	Plugin to DELWAQ to calculate the fate and transport of plastic
DEM	Digital elevation model
DMCR	Department of Marine and Coastal Resources
LAO	Local administrative organization
MFA	Material flow analysis
MNRE	Ministry of Natural Resources and Environment
MPW	Mismanaged plastic waste
MS Excel	Microsoft Excel
MSW	Municipal solid waste
NSO	National Statistical Office
PCD	Pollution Control Department
RTSD	Royal Thai Survey Department
SAO	Subdistrict administrative organization
SDG	Sustainable Development Goal
SWG	Solid waste generated
SWM	Solid waste management
wflow_sbm	Hydrological rainfall runoff model

EXECUTIVE SUMMARY

Thailand, like many countries around the world, is in the midst of a significant plastic waste crisis. In 2019, the Government of Thailand released the *Roadmap for Plastic Waste Management 2018-2030* and is developing the *National Action Plan on Marine Plastic Debris* to alleviate the current impacts and avert future damage caused by marine plastic debris. While these efforts are critical steps toward reining in the country's plastic pollution problem, further insight is needed into where the plastic waste comes from and how it moves in the environment.

This study aims to better understand how plastic waste travels from land-based sources to marine environments by analyzing the material flow of plastic waste in five high-priority catchments (Phetchaburi, Mae Klong, Tha Chin, Chao Phraya and Bang Pakong) and three tourist hotspots (Krabi, Phuket and Ko Samui). The analysis produced reliable results for the generation of plastic waste from land-based sources for all eight locations. The results for waste transport to the marine environment were found to be reliable in only four catchments (Phetchaburi, Tha Chin, Chao Phraya and Bang Pakong) whereas the results for the remaining catchment (Mae Klong) were unreliable due to limited hydrological data.

This study presents the first large-scale assessment in Thailand to integrate national waste generation and waste management performance data with actual hydrological conditions to estimate how mismanaged plastic waste is carried and discharged into the marine environment. The study uses the best available data from national sources including from the Pollution Control Department (PCD), the National Statistical Office (NSO), the Bangkok Metropolitan Administration (BMA) and other sources. Consultation on the methodological approach and available data was undertaken with relevant government agencies, academia and private sector representing plastics and recycling industries.

By mapping the relationship between waste sources, leakage pathways and plastic discharges to the marine environment, this study identifies the most significant hotspots contributing to marine plastic debris and the specific associated waste handling practices (e.g., open dumpsites, household disposal behavior, etc.). Building on previous analysis on the material flow of plastics in Thailand, this study helps inform policy interventions and investments from the Government of Thailand and local administrative organizations to effectively reduce marine debris. The models developed can also help monitor progress relative to environmental factors, such as seasonal rainfall variations.

KEY FINDINGS:
HIGH-PRIORITY CATCHMENTS

- Despite a high collection and recycling rate, a large volume of uncollected plastic waste as well as many unsanitary disposal facilities result in a significant amount of mismanaged plastic waste (MPW):

  › Approximately 11,070 kton of municipal solid waste (MSW) is generated annually—17.4 percent of which is plastic waste.

  › **Formal collection and recycling rates are high with a combined rate of 88.8 percent.**

  › While most collected plastic waste is either recycled or disposed of at a sanitary disposal facility, **nearly a quarter of collected plastic waste is disposed in formal open dumpsites or controlled dumps, or is openly burned/buried.**

  › An additional **214.7 kton/year of plastic waste remains uncollected**.

  › Collected but poorly managed plastic waste and uncollected plastic waste result in **an estimated 428 kton/year of MPW**.

- **Most MPW available for wash-off to rivers and the marine environment (exposed MPW) is generated in rural areas (70.1 percent).**

  › Collection rates are generally much lower in rural areas and this is also where most disposal facilities and open dumpsites are found.

  › Despite high collection rates, **Bangkok is also a significant contributor (18.4 percent) to exposed MPW** due to the large absolute volumes of waste generated, and therefore the large absolute volumes of uncollected plastic waste. **A large amount of uncollected waste in Chao Phraya is disposed directly into waterways.**

- 10 districts (of 247 in total) account for 51.7 percent of the total exposed MPW in the high-priority catchments.

  › Most of the solid and plastic waste is generated in the Bangkok Metropolitan Administration (BMA) area, but most disposal facilities are situated in the surrounding smaller cities and subdistricts.

  › The top 10 MPW contributing districts are all situated near Bangkok and are relatively close to the marine environment.

- Across four high-priority catchments (excluding Mae Klong), on average, **47.6 percent of MPW that ends up in the rivers is discharged into the marine environment**.

  › This represents only about **0.55 percent of the total amount of plastic waste that is generated in these areas**.

  › Higher rates of plastic discharges are associated with the rainy season and lower averages with the dry season.

- An annual average total of 9.3 kton/year of plastic waste is discharged into the marine environment from four high priority catchments (excluding Mae Klong).

  › **This is equivalent to a marine plastic footprint of 0.4 kg/capita/year.**

  › During particularly rainy years this may increase to 14.3 kton/year, while it may be as low as 4.9 kton/year in drier years.

KEY FINDINGS:
TOURIST HOTSPOTS

- **A total of 16.8 kton/year of MPW is generated, with the source varying across the tourist hotspots.**

    › Approximately 381.9 kton of MSW is generated annually—17.2 percent of which is plastic waste.

    › In Phuket, the MPW is derived from uncollected waste but in Krabi, MPW is evenly divided between uncollected waste and disposal at open dumpsites.

    › The model results indicate that in Ko Samui, no (plastic) waste remains uncollected. This is likely unrealistic but is a result of the limited district-specific data available.

- There is an estimated 0.7 kton/year of exposed MPW.

    › Exposed MPW is leaked into the environment primarily as point source in the cities (from unsanitary disposal facilities) and as mostly diffuse sources (from uncollected waste) in the more rural areas.

- **The lack of reliable hydrological data in the tourist hotspots led to unreliable results for the transport of exposed MPW to the marine environment.**

Photo: Shutterstock / NavyBank.
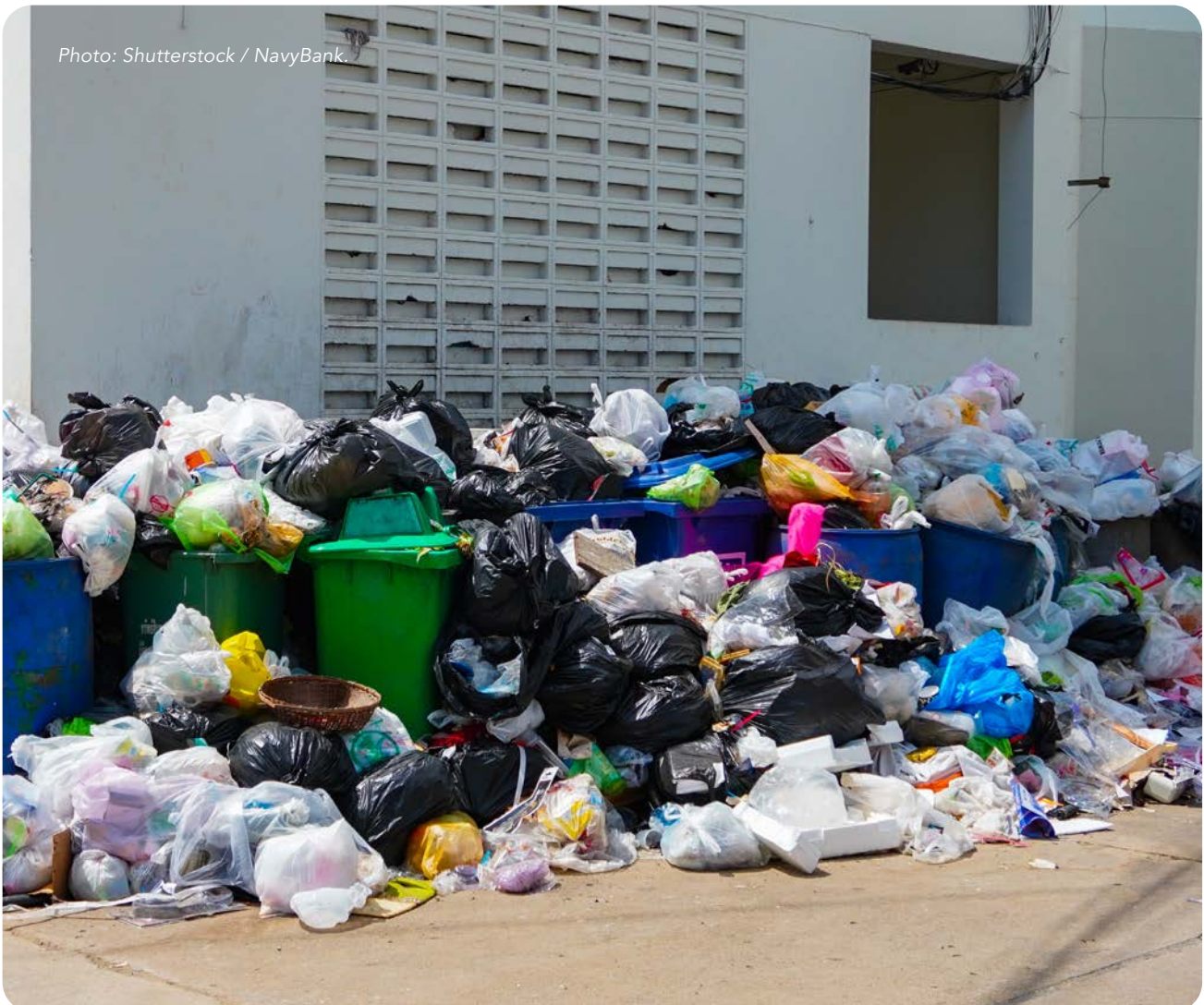
RECOMMENDATIONS

Goal 1: Reduce transport of leaked MPW (downstream in waste chain)

Initially, focus on areas at a close distance from the coast that have been identified as key contributing districts (see Table 14 in section 4.4.1):

- *In urban areas:* Install trash racks in urban drainage systems just before the outlet to a main river or waterway, and clean them daily.

- *In rural areas:* Install trash racks in irrigation canals just downstream from villages.

- *In rivers:* Promote and expand river clean-up initiatives such as the one managed by the BMA in the Chao Phraya River.

- *Overall:* Analyze possible constraints to installing recommended equipment. These measures do not require large financial investments and there may be additional constraints, such as operational costs, preventing progress.

- *Overall:* Monitor plastic waste in the riverine environment as it is intercepted by trash racks.

Goal 2: Reduce MPW generation (mid-stream in waste chain)

- *In urban areas:* Further improve waste collection, particularly in the Chao Phraya catchment.

- *In rural areas:* Develop an efficient and coordinated waste collection system in rural Thailand.

- *Overall:* Invest in well-managed final disposal facilities and upgrade unsanitary disposal facilities (open dumpsites and controlled dumps), giving priority to the facilities near waterways, at close distance to the coast and in key districts.

- *Overall:* Consider introducing city-wide clean-up sweeps just before the start of the rainy season.

- *Overall:* Improve laws and regulations to support the implementation of measures, including enforcing separation at source, monitoring and controlling the operation of waste disposal and capacity building of local authority staff in waste management.

Goal 3: Improve the data and underlying models

- Increase systematic sampling of the solid waste generated and waste composition at the Local Administrative Organization (LAO) or subdistrict levels.

- Undertake field studies to assess the material recovery factor for residential waste pickers.

- Include a specific solid waste management (SWM) question in the National Statistical Office (NSO) annual survey module—for example, one that targets the frequency of waste handling practices.

- Require recycling shops to provide a detailed overview of the amounts of the various types of waste that arrive at the locations and their individual recycling rate.

- Require a daily log to be kept at disposal facilities of how much solid waste arrives at the facility and where each truck comes from.

- Monitor the area around controlled dumps and open dumpsites to detect leakage of (plastic) waste.

- *In the future:* Once better SWM data is available, the modeling can be further improved by collecting hydrological data in the tourist hotspots and small catchments as well as data on the water taken out of rivers for irrigation and water levels in reservoirs.

SECTION 1.
INTRODUCTION

1.1 BACKGROUND

Like the rest of the world, Thailand is facing the challenge of increasing waste generation, especially plastic waste. Although waste management in Thailand has rapidly improved in recent years (Master Plan of Solid Waste Management 2016–2021), residual waste and plastic waste are still major concerns that could have negative effects, including significant inputs to marine debris. In April 2019, to systematically address the plastic waste challenge, the Government of Thailand released the *Roadmap for Plastic Waste Management 2018–2030* and announced the development of a National Action Plan on Marine Plastic Debris to prevent and mitigate plastic waste issues, in line with the Sustainable Development Goal (SDG) 14: "Conserve and sustainably use the oceans, seas and marine resources."

An important step in supporting the Action Plan is to analyze the flow of plastic waste from land-based sources to the marine environment. This report aims to build capacity for material flow analysis (MFA) of plastics in Thailand and to help strengthen the knowledge base of plastic waste with a focus on waste that enters the marine environment. This project in Thailand builds on methodology developed for a similar project conducted in Indonesia (World Bank 2021).

In Thailand, a significant amount of solid and plastic waste leaks into the environment and a large amount of plastic is observed in the rivers and in the marine environment. However, little is known about the quantities that are discharged into the marine environment and where the waste comes from. Insight into the physical flow of mismanaged plastic waste is crucial for guiding effective policymaking decisions.

1.2 ABOUT THE STUDY

The main questions asked by this study include:

- How much plastic waste is being discharged into the marine environment annually?
- Where does this leaked plastic waste come from?
- What can be done to reduce the discharge of plastic waste into the marine environment?

This study is the first large-scale assessment in Thailand where national data of waste generation and waste management performance are integrated with actual hydrological conditions of the rivers—which carry plastic waste from land-based sources into the marine environment. The study applies a methodology and modeling approach (like the one applied elsewhere in the region [World Bank 2021]) to produce estimates of mismanaged plastic waste carried in and discharged by freshwater systems, with high spatial resolution and using the best available data from national sources. Results help establish a baseline of plastic waste discharges into the marine environment in Thailand and help inform the structure, target

activities and monitoring and evaluation framework of the Action Plan.

By incorporating the interdependency between sources, leakage pathways and riverine plastic discharges, this integrated approach pinpoints the most critical hotspots of plastic leakages and the specific waste handling practices that generate them (e.g., open dumpsites or households disposing of waste in waterways). This approach also quantifies their relative contribution to the plastic discharge into the marine environment. Additionally, leakages and hotspots can be linked to geographical areas (e.g., administrative areas or (sub) districts) to better differentiate between regions that need special attention. Most importantly, these results can help set local priorities, define interventions and prioritize investments, and can effectively reduce marine debris while monitoring progress relative to environmental factors (e.g., rainfall, discharge and annual/seasonal variations), which are quantitatively accounted for.

This report will discuss issues related to data availability, knowledge gaps, assumptions and validation, and will provide recommendations for future improvements that can lead to better estimates and more useful results. Applying a similar approach in the future will help to monitor progress toward the implementation of the Action Plan and observe the effectiveness of national and local measures in preventing new inputs of plastic waste into the sea.

This report builds on previous studies on MFA of plastic in Thailand. Further details on these studies are provided in Appendix A.

1.2.1 Scope of the Study

Marine plastic debris originates from many different sources, including both land- and sea-based activities, and is often related to the mishandling of municipal, industrial and agricultural solid waste, as well as loss of materials such as cargo or fishing gear.

This study focuses on land-based sources of marine plastic debris resulting from municipal solid waste. Plastic waste that originates from maritime activities such as fishing and shipping (sea-based sources) as well as any other industries that are not accounted for in the municipal solid waste data used as input for the study's estimates is excluded.

While acknowledging that smaller plastic particles (including microplastics) are of high interest and concern, this study considers only the larger fraction of plastics as a starting point. It excludes sources—such as weathering of textiles, paints and tires—that generate microplastics and can reach the marine environment through sewers and atmospheric deposition in addition to waterways. Although the modeling accounts for processes of fragmentation as plastic is carried from land into the sea, the results do not make a distinction between plastic sizes or plastic types. Only the total plastic mass that is discharged into the marine environment is considered in this study.

The study focuses specifically on five high-priority catchments that discharge into the upper Gulf of Thailand (Phetchaburi, Mae Klong, Tha Chin, Chao Phraya and Bang Pakong) and three tourist hotspots (Krabi, Phuket and Ko Samui). The geographic scope is shown in Figure 1 and some basic administrative information of the focus areas is provided in Appendix B.

1.2.2 Outline of the Report

This report is designed to assess how much mismanaged plastic waste (MPW) is flowing into the Gulf of Thailand. In Chapter 2, the approach and methodology are presented and explained, and the various definitions used in the report are discussed. The different steps in the models and the data used to develop the models and databases are also described. The data gaps and the impact assumptions may have on the final results are also identified.

The results of the models are presented in Chapter 3. The solid waste management model results are provided first, followed by the results from the fate and transport models. Section 3.3 describes the validation of the model results and situates the results among other relevant studies.

Chapter 4 provides the final conclusions and recommendations, which offer priority lists and examples of recommended measures to reduce marine debris. Specific recommendations are also provided to address identified data and knowledge gaps.

Additional background information and more detailed results, validation and recommendations are available in the Appendices.

Figure 1.
GEOGRAPHIC SCOPE OF THIS STUDY
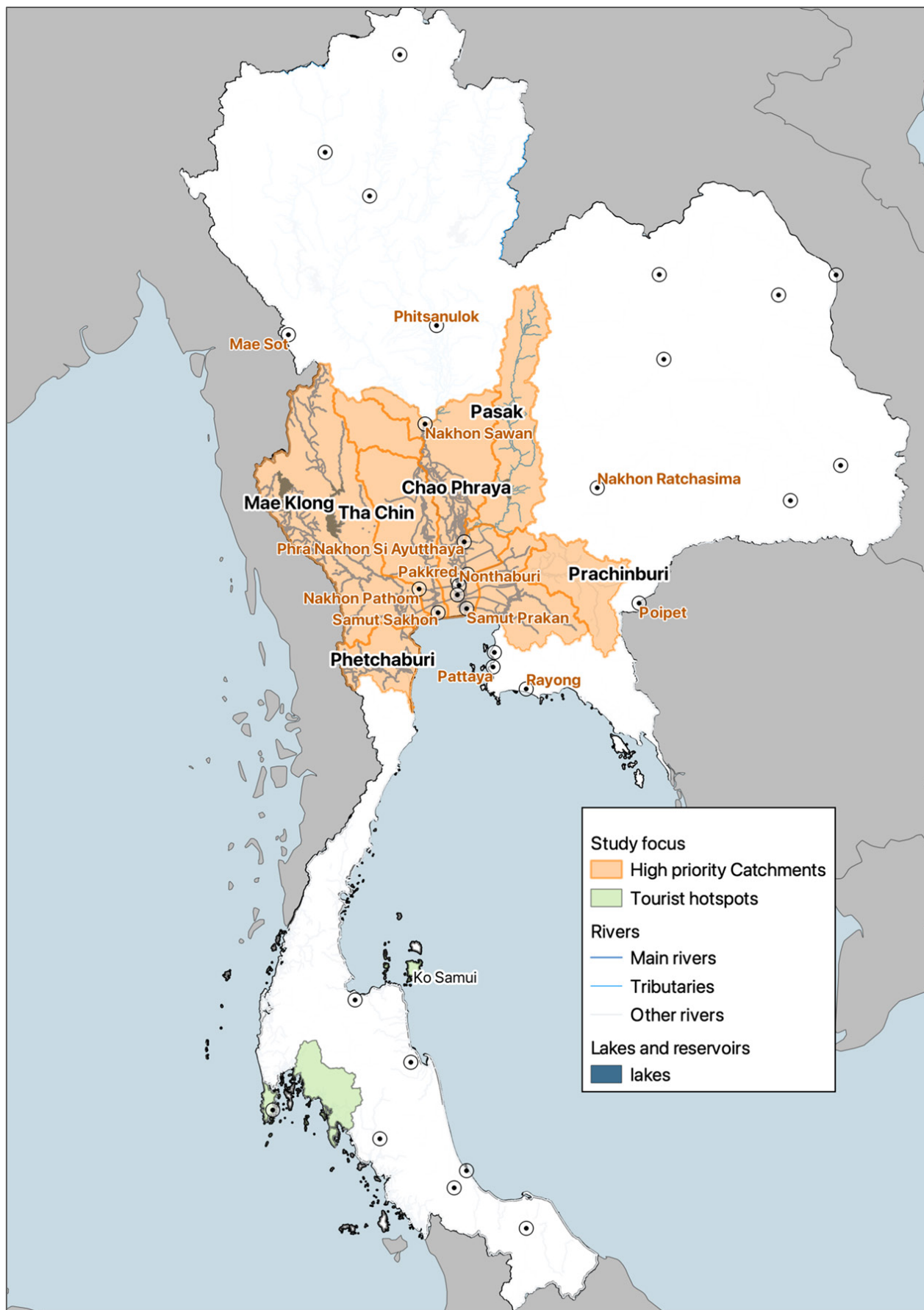
Source: Original figure for this publication.

SECTION 2.
MODELING APPROACH AND METHODOLOGY

In this chapter, the general approach for the modeling of the material flow of plastic waste in Thailand is described. The relevant processes, tools and modeling methodologies are briefly described in sections 2.1, 2.2 and 2.3. Further description of the underlying approach can be found in World Bank (2021).

2.1 GENERAL APPROACH AND DEFINITIONS

A schematic of the data and models that make up the modeling approach is shown in Figure 2. A Solid Waste Management (SWM) model was developed to quantify the amount of plastic emitted to the environment by human activity and demonstrate the various sources and pathways of plastics from origin to disposal. This model provides an estimate of the MPW leaked into terrestrial and riverine environments, as well as the locations of these leakages—which are inputs for the fate and transport models.

Wash-off is the driving factor for transport of plastics to surface water, so a hydrological rainfall runoff model (wflow_sbm) is used with a fate and transport model (D-Emissions) to calculate the amount of plastic leakage to the environment that is washed off the land and into rivers. The transport of plastic through the river network is then modeled with a combination of wflow_sbm and DELWAQ to determine the final amount of plastic debris that reaches the marine environment.

The general approach for this study involves integrating Thai data on SWM with hydrology to model the flow of plastic waste generated on land, leakages from different land-based sources into waterways and transport through rivers into the marine environment (Figure 3).

Clear definitions of the different fractions of plastic waste are essential for proper mass balance computation. See Box 1 for the key definitions used in this study. The material flow diagram in Figure 4 provides insight into the physical flow of plastic waste and the fractions of waste that are transferred down the waste chain or reach a specific site or domain as a final destination. The individual rates and figures are determined in the various steps of the modeling train.

Figure 2.
SCHEMATIC REPRESENTATION OF THE MODELING APPROACH
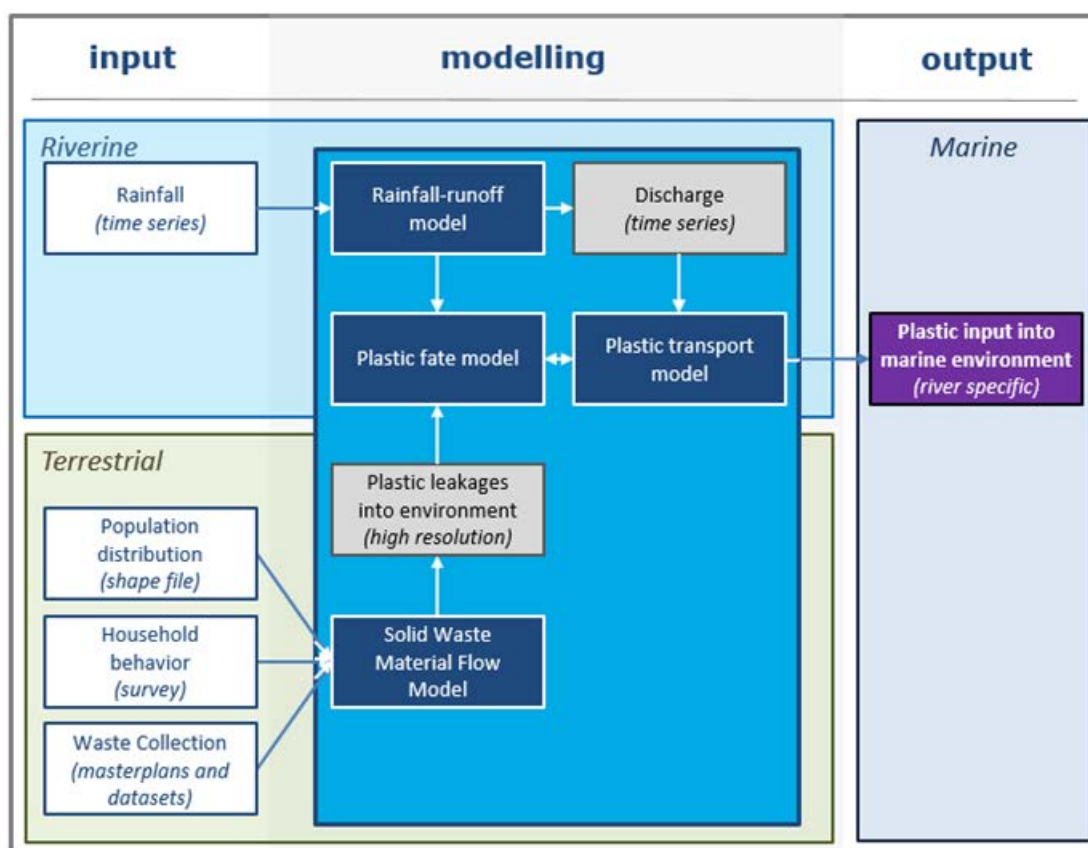
Source: Original figure for this publication.

Figure 3.
CONCEPTUAL FRAMEWORK FOR MODELING MATERIAL FLOW (GREEN/LIGHT BROWN), LEAKAGES (RED) AND WASH-OFF/TRANSPORT OF PLASTIC WASTE FROM LAND-BASED SOURCES VIA RIVERS (BLUE)
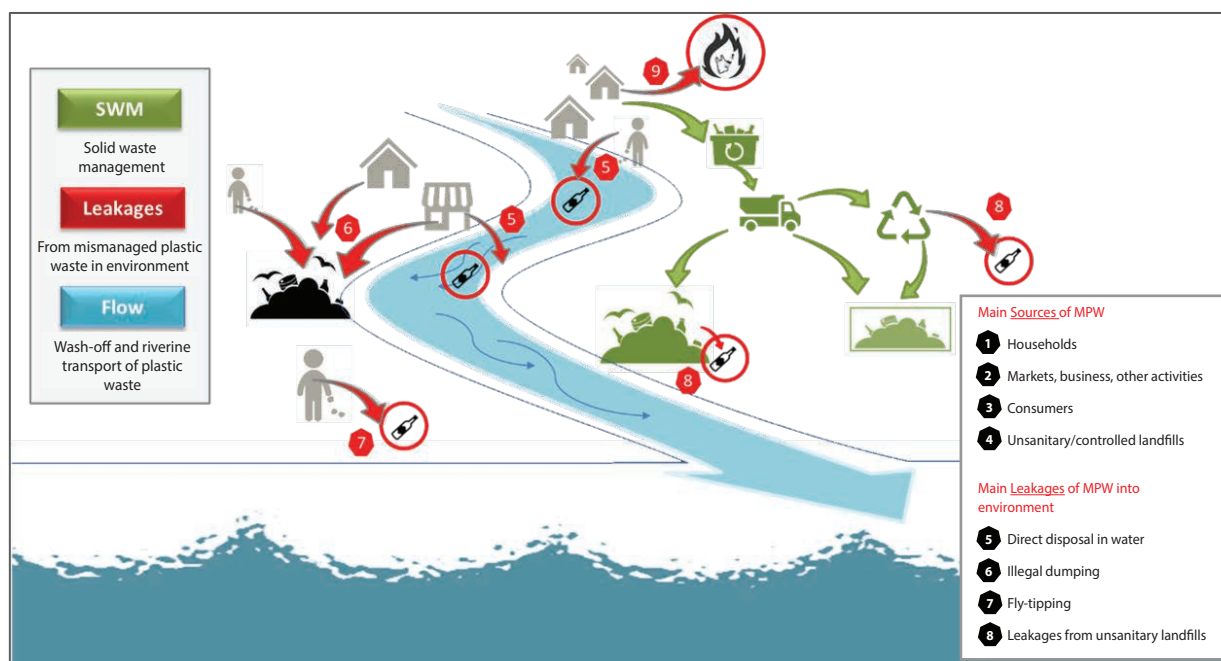
Source: World Bank, 2020.

Figure 4.
SANKEY DIAGRAM PROVIDING INSIGHT IN THE PHYSICAL FLOW OF WASTE DOWN THE WASTE CHAIN FROM SOURCE TO SEA
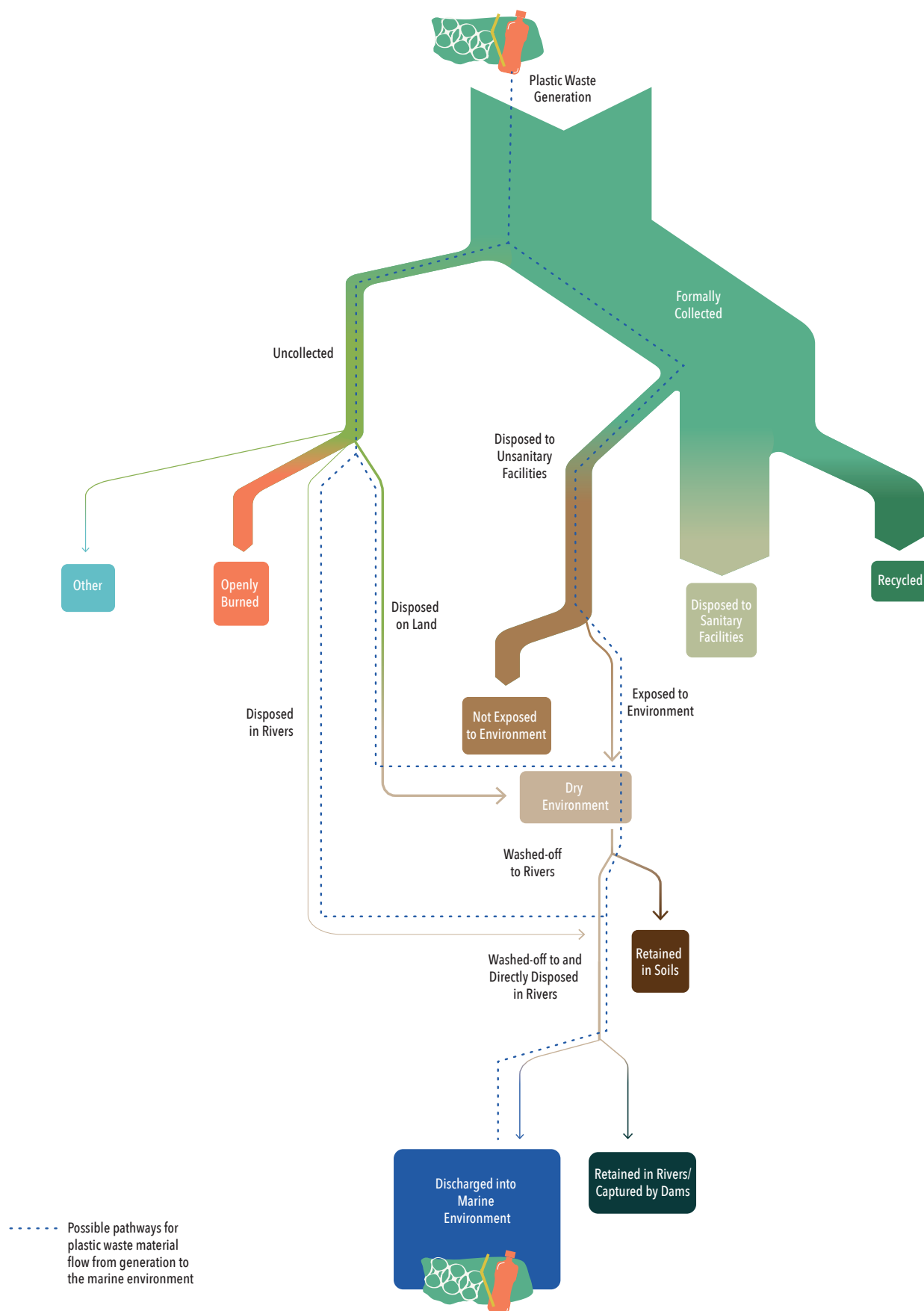
Source: Original figure for this publication.

BOX 1.
DEFINITIONS
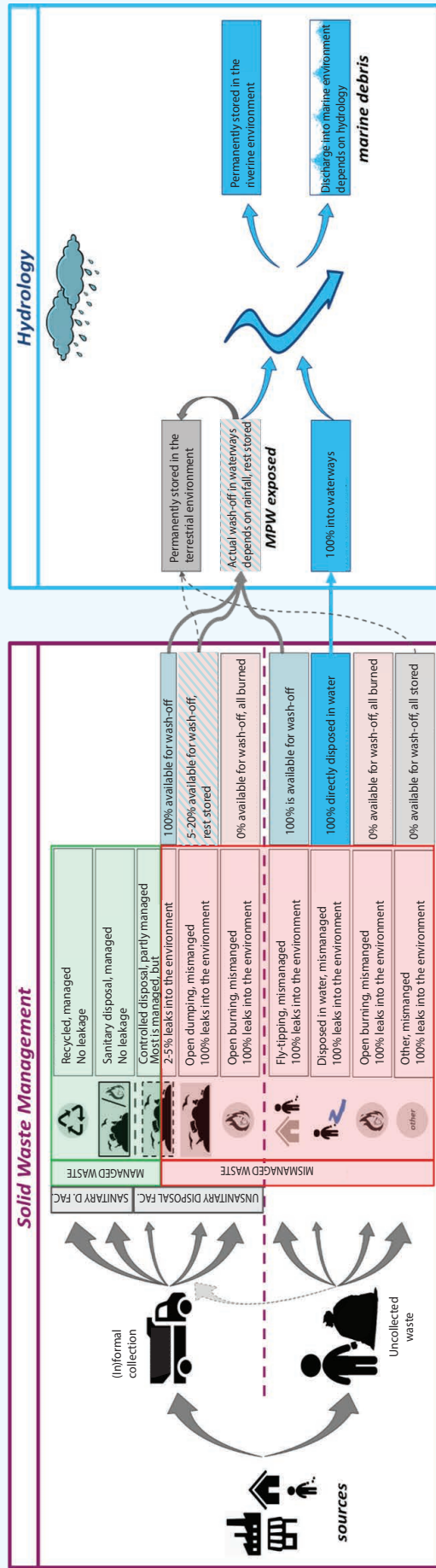
SOURCES: Economic sector, human activity or infrastructure from which waste is released into the environment. The means of release **(leakage)** are specified to indicate the mechanism or the way the waste item leaves the intended cycle (as in Veiga et al. 2016). Examples: **direct disposal in water** (leakage) from **households** (source)

UNCOLLECTED WASTE: All waste that is left **uncollected** (by both formal and informal collection).

(UN)SANITARY TREATMENT FACILITIES: Sanitary treatment facilities are facilities where solid waste is handled and treated in such a way that it does not result in leakage into the environment. At unsanitary treatment facilities, leakages are expected.

LEAKAGES: Flow of plastic waste into the environment (or from one environmental compartment into another), from a **particular source**, either by accidental (e.g., loss) or purposeful release (e.g., littering, direct disposal in water) or by action of physical factors such as rain and wind. The pathway should be further specified as "leakages into waterways" to indicate the fraction that ends up in rivers through direct disposal or as a result of wash-off. All leaked plastic results from MPW, but not all MPW leaks into waterways (e.g., it can be burned).

MPW: The fraction of plastic waste that is not adequately collected, treated or contained, and can or will end up in the environment. Specifically, MPW accounts for all the uncollected plastic waste; all losses from collection and recycling; all plastic waste that ends up in open dumpsites and is openly burned or buried, as well as the plastic

waste that leaks from controlled dumps (which have some level of containment but are not as rigorous as sanitary landfills, a rate is attributed).

MPW has a likelihood of ending up in the terrestrial environment and/or in waterways depending on the conditions in which it is handled, contained and how much is exposed to rainfall (see Exposed MPW).

EXPOSED MPW (AVAILABLE FOR WASH-OFF): The fraction of MPW that is exposed to rainfall and can be transported by rain (i.e., that can leak from terrestrial environment into waterways). (Burned and buried MPW are not considered exposed to rainfall.) Whether this will end up in waterways will depend on the permeability of the soil, the inclination of the terrain and the distance to waterways. From point sources of MPW (e.g., controlled dumps or open dumpsites) a **wash-off availability rate** is attributed to determine the potential maximum leakage into waterways.

MARINE DEBRIS: Also referred to as marine litter, is any processed or synthetic material or item that ends up in the marine environment, directly discarded or lost from maritime activities (sea-based for example, fishing and shipping), direct littering at the coast or carried from land-based activities via runoff, river outflows, etc. (GESAMP 2019). **Plastic marine debris** constitutes the plastic fraction of marine debris, which tends to be the predominant material. Note that this study focuses only on plastic marine debris that originates from land-based sources.

The study includes a sequential set of analyses and uses different types of data and tools (described in more detail in 2.2 and 2.3). The overall approach can be summarized as follows:

1. **Leakages of MPW:** Population and solid waste handling and management data (e.g., plastic waste generated, collected, treated and handling practices) are used to assess the plastic waste flow and estimate amounts of mismanaged plastic generated within a local administrative organization (LAO) and/or (sub)district. Any plastic waste that is not properly collected and treated can be **directly disposed of in waterways or disposed of and leaked into waterways via the terrestrial environment**. A static database is created which is considered representative for the 2018 situation based on available data obtained from the Pollution Control Department (PCD), the LAOs, the Bangkok Metropolitan Administration (BMA), and the National Statistical Office (NSO). Based on the available data, three scenario datasets are constructed to represent low, mid and high estimates for exposed MPW.

2. **Hydrological factors:** Runoff as a result of rainfall and river flow are the driving forces that can **wash off plastic waste from land into waterways and transport it downstream through rivers**. Runoff from rainfall and river flow is simulated using a hydrological model (wflow_sbm). The process is simulated considering the local topographical conditions, soil-type, land-use and spatially and temporally variable meteorological data. A spatially and temporally variable representation (time series) of runoff and discharge is created based on a historical rainfall time series obtained for January 2010 to December 2018 and includes both dry years (2014 and 2015) and wet years (2011, 2013 and 2017).

3. **Plastic fate and transport:** Any MPW that is **leaked into the terrestrial environment** is exposed to degradation (weathering, fragmentation into smaller particles), burial in soils and physical barriers that obstruct plastic from washing off. The excess plastic waste is exposed to rainfall and may wash off through runoff, where it is then transported to a river, stream or lake. MPW that is washed off to and **disposed of directly in waterways will be transported downstream toward the marine environment** unless it is retained in the river—either by settling to the riverbed or getting captured by natural or artificial obstacles such as vegetation or dams. This is simulated by modeling the wash-off (D-Emissions) and riverine transport of plastic waste with a fate and transportation model (DELWAQ).

As a result, a spatially and temporally (based on hydrological variations during the nine-year period) variable representation of the transport and fate of plastic waste from land-based sources to the marine environment can be constructed as a reflection of certain waste generation (three scenarios: low, mid, and high) and waste management characteristics from the communities that live within the catchment.

2.2 MODELING LEAKAGES OF MISMANAGED PLASTIC WASTE FROM LAND-BASED SOURCES

This section describes the approach to assess and quantify potential leakages of MPW from land-based sources.

The primary data source for this model is data from the PCD, followed by data from the NSO, BMA and other sources. The PCD holds the essential data to assess the waste flow through the formal collection and recycling part of the waste chain while NSO holds key information on the treatment of uncollected waste. There is no information on the contribution of the informal sector on the flow of waste in Thailand. A summary overview of the data sources, the data limitations and the assumptions are provided in Table 1.

2.2.1 Overview of the SWM Model

The SWM model for this project is developed specifically for Thailand. It builds on the unique Thai context, the organization of the Thai administration and the SWM structure. The model is based on the complex solid waste material flow diagrams of the PCD and three leading Thai universities. Including the insights gained from the national surveys, the model shows how mismanaged and uncollected plastic waste may end up in the environment. The SWM model specifically focuses on potential leakages of mismanaged waste, beginning at the point of solid waste generation in the material flow diagram. It does not specify or quantify the upstream processes.

Figure 5.
SWM MODEL FLOW SCHEMATIC CONSTRUCTED FROM PCD AND NSO ADAPTED SCHEMATICS
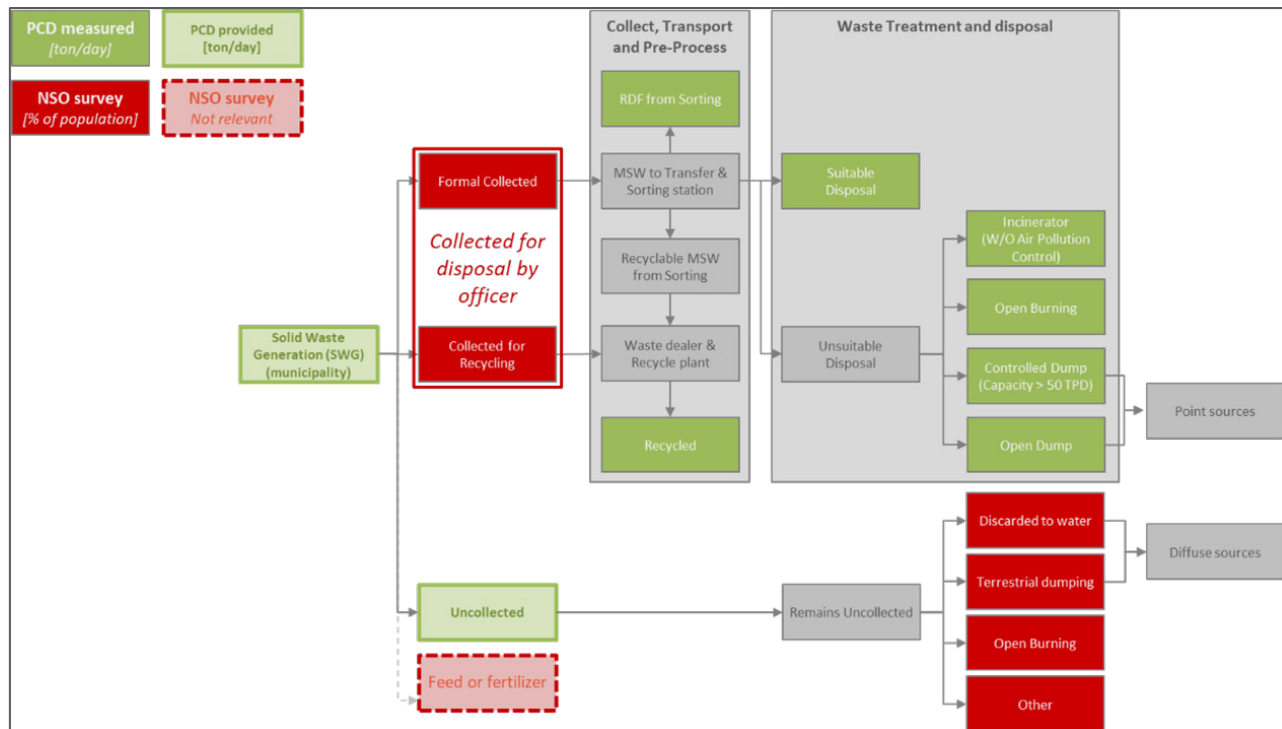
Source: Original figure for this publication.

Thailand produces a large amount of solid waste (estimated by Kojima (2019) at 26,850 kton in 2016), but not all waste is collected (PCD 2019; Kaza et al. 2018) and a significant amount ends up in the environment (NSO 2020). As illustrated in Figure 3, the two driving forces behind MPW in Thailand are inadequate SWM practices (with final disposal in unsanitary facilities) and inadequate treatment and disposal behavior (i.e., how individuals and households handle their waste, in particular the uncollected portion). Mismanaged solid waste and MPW leaks into the environment through these pathways. MPW consists of all uncollected waste, all waste that is disposed of in open dumpsites and the fraction that is available for wash-off from controlled dumps. Through the specific locations of the formal (unsanitary) treatment facilities (point sources), the spatial distribution of mismanaged collected waste is captured. The spatial distribution of uncollected waste and the inadequate handling thereof (diffuse sources) is captured through the spread of the population over subdistricts.

A schematic of the SWM model flow diagram is presented in Figure 5. All the SWM data is compu-

tationally processed with an MS Excel-based SWM model[1] developed as part of this project.

2.2.2 Determining MPW Available for Wash-off

The first step in determining the MPW available for wash-off (exposed MPW) is to estimate solid waste generation and formal collection rates. Solid waste generated per capita is estimated by interpreting and filtering solid waste generation figures at the LAO level obtained from LAOs and the PCD, along with population figures from the Royal Thai Survey Department (RTSD). There is no data available to differentiate the solid waste generated (SWG) between various sources, including differentiating between waste from residents and tourists. The plastic fraction is estimated based on waste composition figures from the PCD and BMA. Formal collection figures, including for recycling, are directly obtained from the PCD and BMA.

The final destination of collected solid waste and plastic waste is then determined based on data from

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1   Microsoft Excel (MS Excel) was chosen as the spreadsheet processor due to the familiarity of many people with MS Excel for data processing. This familiarity is important for smooth adoption and knowledge transfer of the SWM model to the Ministry of Natural Resources and Environment (MNRE) for extension and regular updating of the model.

the PCD. This may include sanitary disposal facilities (e.g., sanitary landfills) without any leakage to the environment but may also include unsanitary disposal facilities (e.g., controlled landfills or open dumpsites) which may leak into the environment.

Next, the amount of uncollected waste is estimated through the difference between the total amount of SWG and the total amount formally collected (through formal collection and recycling). Waste handling practices for uncollected waste are based on an interpretation of the national survey[2] (see Box 2) and are used to estimate diffuse leakages from the uncollected waste fraction directly into waterways and into the environment.

Lastly, while some MPW that is leaked into the environment is exposed to natural forces that may mobilize this waste and move it to a waterway, not all MPW is exposed to these forces (e.g., waste that is buried or burned). In locations where high concentrations of MPW can be found (e.g., open dumpsites) only a small fraction of the total amount of the waste disposed is exposed to the forces that could cause wash-off. In the model this is captured by an "available for wash-off" parameter. The type of formal disposal facility is used to estimate the amount of waste that may be exposed to wash-off at point sources (exposed MPW), with the fractions based on expert judgement due to a lack of scientific data. See Box 3 for more details.

To account for uncertainties, three figures (low, mid and high) are estimated for the SWG per capita and the plastic content. At the subdistrict and disposal facility levels, this results in specific low, mid and high estimates of mismanaged waste, feeding into three scenarios for leakage patterns in the focus areas. These three scenarios are considered representative for a best estimate (midestimate) and a likely range (low and high estimates).

As the SWM data are analyzed on a spatial scale of subdistrict, this is also the spatial scale of the derived leakage estimates. For catchment-scale modeling this has been shown to be adequate in resolution for understanding leakage patterns and analysis of possible mitigation scenarios. The tourist hotspot locations chosen for this study are much smaller in area and therefore much more sensitive to localized waste handling practices and small-scale hydrological events. To account for lack of resolution in the SWM data, the calculated leakage rates are mapped to a high-resolution population dataset.[3] This raster dataset is composed from satellite imagery to approximate the locations of buildings as a proxy for population density. In this way, the exact location of SWM leakage can be better approximated for these small catchments.

BOX 2.
NSO SOCIOECONOMIC HOUSEHOLD SURVEY

The socioeconomic household survey was conducted by the NSO in 2018. This household survey provides key information to validate collection data and to quantify handling practices for uncollected waste.

The survey asked people in the household how they handle their municipal solid waste (MSW). This multiple-choice question included the following potential responses:

1. Officially collected by government

2. Openly burning

3. Brought to landfill

4. Feed the animals at home

5. Composting/use as fertilizer at home

6. Dispose into river/canal

7. Dispose in public space

8. Others

The NSO summarized the responses and reported the results as a percentage for each province.

Choices number (1) and (3) are considered as formal collection for formal treatment and recycling. The rest are considered uncollected and are managed by the people in the household. The options for animal feed (4) and composting (5) were omitted since because they are not relevant to plastic waste. The remaining options are recalculated to find the relative percentage of each for the handling of uncollected waste. These percentages are used to estimate the fraction of uncollected waste that is available for wash-off.

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2   Household Socio-Economic Survey Project 2018, the National Statistical Office (NSO).

3   https://data.humdata.org/dataset/thailand-high-resolution-population-density-maps-demographic-estimates (accessed July 2, 2020).

BOX 3.
MPW AND EXPOSED MPW

At locations where high concentrations of waste can be found, it is assumed that at any point in time only a fraction of the amount of waste is exposed to the natural forces that may lead MPW to wash-off. As a result, not all waste that is disposed on a controlled dump or open dumpsite ends up exposed and available for wash-off.

At controlled dumps it is assumed that only the lighter fractions of (plastic) waste are leaked into the environment (through various means) and therefore considered "mismanaged." It is estimated that from controlled dumps, 2–5 percent (with a mid-point estimate of 3 percent) of (plastic) waste may leak into the environment (through mobilization by wind, rain, animals, etc.). This percentage is considered exposed to rainfall and available for wash-off. For the three scenarios (low, mid and high) the following leakage rates are used in the SWM model: 2 percent for the low scenario, 3 percent for the mid scenario and 5 percent for the high scenario.

At open dumps, all waste is considered to have leaked into the environment and is therefore considered mismanaged. However, only waste on the top layer and at the foot of the dumpsite is considered exposed to rainfall and could be mobilized (see Figure B3.1 below). It is estimated that

at open dumpsites this accounts for 5–20 percent (with a mid-point estimate of 10 percent) of (plastic) waste that is at any one point in time exposed to rainfall. Only this amount is then available for wash-off. For the three scenarios (low, mid and high) the following exposure rates are used in the SWM model: 5 percent for the low scenario, 10 percent for the mid scenario and 20 percent for the high scenario.

From sites where (plastic) waste is openly burned, it is assumed that all waste leaks into the environment and is therefore mismanaged. However, it is also assumed that no (macro) plastics are present after burning and that 0 percent of (plastic) waste is available for wash-off from locations where waste is openly burned. Similarly, for buried (plastic) waste, it is assumed that 0 percent of (plastic) waste is available for wash-off.

Whether exposed MPW will wash off depends on actual rainfall and is calculated by the fate and transport model (D-Emissions). The exposed MPW amounts are simulated as point sources which are then modeled as an amount in one grid cell of the fate and transport model. This is further explained in section 2.3.

Figure B3.1.
WASTE EXPOSED TO RAINFALL AND POTENTIALLY MOBILIZED

Top view

Side view

And only blue part will be considered for % wash off availability

Table 1.
SUMMARY OF SWM MODEL DATA SOURCES, LIMITATIONS AND ASSUMPTIONS

Indicator/ subindicators	Data source	Data limitations	Assumptions made	Expected impact of assumptions
(1) Total SWG (population × solid waste generated per capita)				
Population	RTSD	None	Population dataset from 2018 used	—
SWG per capita	PCD guideline (2019) LAO (2020) NSO survey (2019)	No detailed SWG per capita available at LAO/ subdistrict level	One estimate is based on LAO reported SWG figures[4] with outliers (10% smallest and 10% highest) replaced with the average SWG per capita figure for the province. One estimate is based on LAO reported formal collection figures and NSO collection rates. SWG per capita figures were multiplied with a factor to obtain collection rates more in line with NSO results at provincial level. One estimate is based on the PCD guideline. Subdistrict results are arranged to get low, mid, and high estimates.	High uncertainty translates into a wide range of estimated SWG and very high uncertainty on uncollected waste. Further downstream in the material flow model this will result in a wide range for (exposed) uncollected waste. Three scenarios are generated for SWG and represent low, mid, and high estimates.
(2) Total plastic waste generated (SWG x plastic content)				
Plastic content	PCD (2004) BMA (2007–2019)	There is no underlying data from PCD estimates. PCD estimates differentiate according to region and LAO type. BMA differentiates between non-recyclable and recyclable plastics.	Mid estimate is based on PCD estimates. Low estimate is based on the average for non-recyclable plastic over the period 2017–2019 (BMA data). High estimate is based on the average for non-recyclable plastic over the period 2010–2014 (BMA data).	This results in a wide range for plastic content and subsequently leads to a wide range for (exposed) MPW (from both collected and uncollected waste). Therefore a wide range for plastic discharge estimates is expected.
(3) Total plastic waste collected (formally collected + recycled)				
Total (plastic) waste formally collected	PCD database[5] (2019) BMA database (2019) Both representing 2018 collected waste	No data available on origin of waste disposed at formal disposal sites. BMA dataset is aggregated data at Bangkok provincial level and does not provide insight at district level.	Solid waste collected is proportionally distributed over the various formal treatment facilities according to the formal capacity. Solid waste is collected and disposed within the same province (except for Bangkok province).	May lead to net "import/export" of waste in the model because of discrepancies between estimated total SWG and installed capacity in an LAO/subdistrict. Potential over/under-estimation of MPW at LAO/(sub)district level because all waste

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4   Although reported as SWG, the figures are derived from the collected waste figures directly.
5   Thailand Municipal Solid Waste Management Database. URL: https://thaimsw.pcd.go.th/report1.php.

Indicator/ subindicators	Data source	Data limitations	Assumptions made	Expected impact of assumptions
				with final destination of the specific LAO/(sub)district is used to estimate MPW and MPW per capita for that LAO/(sub)district.
				There is little to no effect on discharges from catchments as "import/export" differences are mainly in the upstream boundaries of the catchment.
				Limited uncertainty on MPW from point sources.
				Results for Bangkok are not representative at (sub)district level and should only be interpreted with caution at provincial level.
Collected by waste pickers	*No data available*	*No data available*	*Not considered*	Collection by waste pickers is generally very small. It is expected that the impact on the results is negligible.
(4) Total plastic waste uncollected				
Handling practices for uncollected waste	Household Socio-Economic Survey Project 2018, NSO, as the most recent data for household solid waste practices	Data is only available at provincial level. Only multiple choice where respondents can choose multiple options is available. Survey is based on a small sampling size.	Provincial value is representative at subdistrict level.	Discharges of catchments are representative, but de-aggregated results to LAO level are unreliable.
(5) Total recycled plastic waste (recycled from waste dealer and recycle plant)				
Recovery from recycling shops	PCD database BMA database	No data is available on origin of waste recycled. No data is available on effective recycling fraction. No validation dataset is available.	It is assumed that all waste collected at recycling shops is recycled and that there are no recycling losses from the shops.	There is potential over/underestimation of MPW. However, this leakage source is small and it should not have a significant influence on the discharge results.

Indicator/ subindicators	Data source	Data limitations	Assumptions made	Expected impact of assumptions
(6) Total plastic waste disposed to final destination (disposal to sanitary landfills + controlled dumps + official dumpsites + total recycled plastic waste)				
Disposal to sanitary disposal facilities (sanitary landfills, incinerators, integrated facilities, etc.)	PCD gate data PCD facility classification	No data is available on origin of waste disposed at formal treatment facility.	All waste is formally collected and is evenly distributed over the available treatment facilities according to installed capacity.	There is no effect on the estimated discharges, but there is uncertainty surrounding the actual flow of (plastic) waste.
Disposal to unsanitary disposal facilities (controlled dumps)	PCD controlled dump data	Same as above.	Same as above.	Same as above.
Disposal to unsanitary disposal facilities (open dumpsites)	PCD open dumpsites data	Same as above.	Same as above.	Same as above.
Disposal to unsanitary disposal facilities (open burning)	PCD open burning data	Same as above.	Same as above.	Same as above.
(7) Total MPW ([total uncollected plastic waste + losses from collection] + total plastic disposed of to open dumpsites + leakages from controlled dumps)				
Disposal to sanitary disposal facilities (sanitary landfills, incinerators, integrated facilities, etc.)	Same data as numbers (4) and (6)	No information on actual leakages is available.	It is assumed there is 0% leakage of waste.	If there is a small amount of plastics leaked at these facilities, it may result in a slight underestimate of MPW.
Disposal to unsanitary disposal facilities (controlled dumps)	Same data as numbers (4) and (6)	No information on actual leakages is available. Expert opinion[6] is used upon initial consultation with relevant agency.	There are three ranges of leakage of plastic waste going to controlled dump: low (2%), mid (3%) and high (5%). *Rationale*: Waste is mostly light plastic bags and other waste that may be blown away and leak into the environment.	The range is considered realistic to capture the uncertainties and the resulting MPW range is wide.
Disposal to unsanitary disposal facilities (open dumpsites)	Same data as numbers (4) and (6)	No information on actual leakages is available.	It is assumed that 100% leaks into the environment.	There is no effect.

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6   There are no scientific studies available to estimate potential leakage rates from various disposal facilities. Therefore, similar values have been considered as were used in a similar material flow study for Indonesia (World Bank 2021). Although it was not possible to compare the conditions at disposal facilities on the ground, due to the absence of verified local Thai estimates and the fact that the estimates used in the study for Indonesia were provided by solid waste management experts, also based on global experience (including personal observations at disposal facilities in Thailand), it is believed these are best estimates that can be used until better (local) estimates based on scientific research become available.

Indicator/ subindicators	Data source	Data limitations	Assumptions made	Expected impact of assumptions
Disposal to unsanitary disposal facilities (open burning)	Same data as numbers (4) and (6)	No information on actual leakages is available.	It is assumed that 100% leaks into the environment.	There is no effect.
(8) Total exposed MPW (available for wash-off) (from sanitary landfills + controlled dumps + formal dumpsites + uncollected plastic waste)				
From unsanitary disposal facilities— controlled dumps (leakage)	Calculation: Total plastic waste disposed Landfill coordinates from PCD	Expert opinion[6] is used upon initial consultation with relevant agency.	It is assumed that 100% of MPW (leaked plastic waste) exposed is available for wash-off. When landfill coordinates are available they are considered as point source.	There is no effect.
From unsanitary disposal facilities—open dumpsites	Calculation: Total plastic waste disposed Open dumpsite coordinates from PCD	Expert opinion[7] is used upon initial consultation with relevant agency.	There are three ranges for exposed MPW (available for wash-off) going to open dumpsites: low (5%), mid (10%) and high (20%). Rationale: Only the top layer and the foot are exposed to the elements (rain and wind) and may be transported. When open dumpsite coordinates are available they are considered as point source.	The wide range for exposed MPW from open dumpsites is considered realistic to capture the uncertainties and the resulting discharge range is wide.
From unsanitary disposal facilities—open burning	Calculation: Total plastic waste disposed Open burn-site coordinates from PCD	Expert opinion is used upon initial consultation with relevant agency.	Complete burning is assumed with 0% of MPW exposed (available for wash-off).	There are a limited number of locations, which may result in underestimation of discharge range.

2.3 MODELING WASH-OFF AND TRANSPORT OF PLASTIC WASTE TO THE SEA

2.3.1 Rainfall-runoff Modeling

The rainfall-runoff process is the main driver of the wash-off of plastic waste. The main hydrological component is the direct surface runoff. This process happens when the rainfall cannot infiltrate the ground. This is often the case in high-density paved areas (e.g., urban areas with dense road network) that have reduced infiltration capacity of the soil and during high-intensity rainfall that exceeds the infiltration capacity of the soil.

Direct surface runoff transports the plastic waste over the surface toward the (small) rivers. To accurately simulate this process, a detailed catchment model is needed. It should be able to:

- Distinguish between different land cover and soil types

- Relate these land cover types to different soil infiltration capacity rates

- Simulate the surfaces runoff toward the (small) rivers

To simulate the rainfall-runoff process for the catchments in Thailand, wflow_sbm models are setup. Wflow_sbm is a fully distributed, physically-based hydrological model.

The main relevant processes included in the wflow_sbm model are:

- Rainfall interception

- Soil-related processes (infiltration, evaporation)

- Routing of the sub-surface flows

- Routing of the surface flows

- Simple reservoir and lake routing processes

An overview of the relevant processes in the wflow_sbm model is shown in Figure 6.

Figure 6.
OVERVIEW OF THE WFLOW_SBM PROCESSES

Source: https://deltares.github.io/Wflow.jl/dev/.
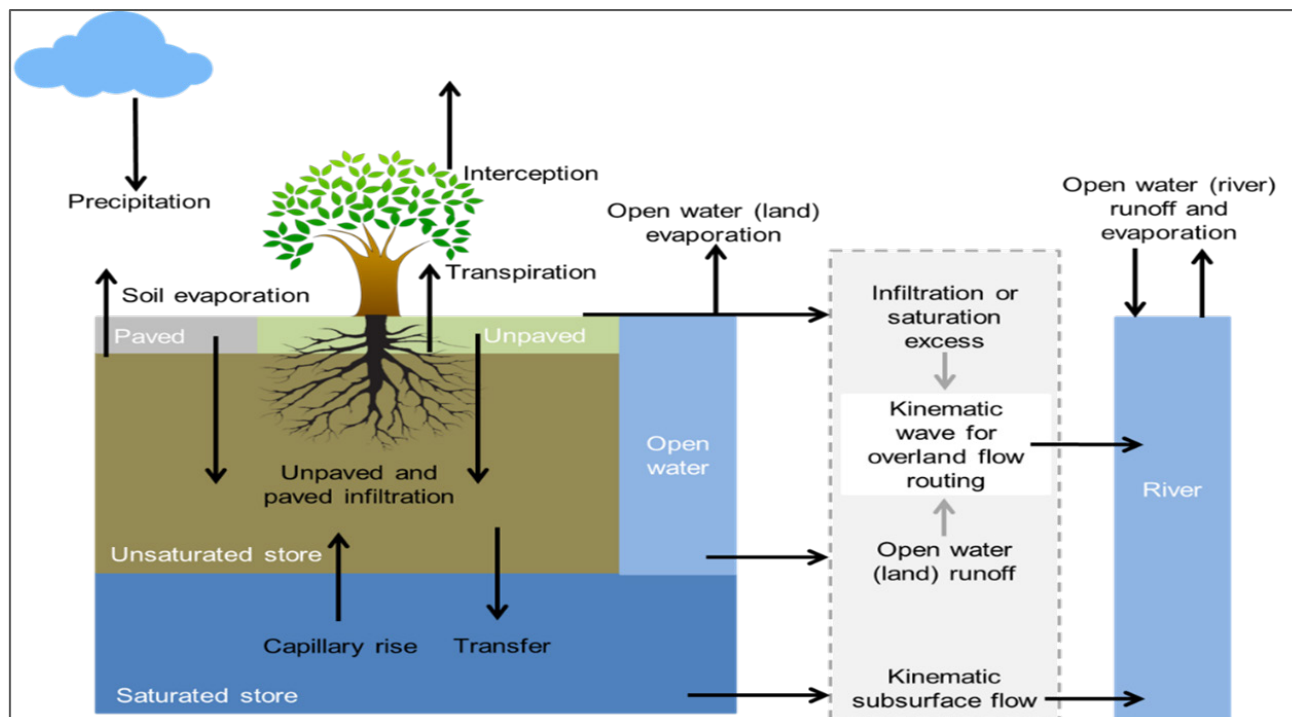
Since the wflow_sbm model is fully distributed, all input parameters can be provided as spatially varying parameters. Parameters can be directly linked to land cover types and/or soil types. In this way, models are derived with a strong link to observed features of the landscape and processes are simulated based on the best available knowledge of the physical system.

The hydrological models are set up for the five mainland basins (Chao Phraya, Tha Chin, Bang Pakong, Mae Klong and Phetchaburi) as well as for the three tourist hotspots (Krabi province, Phuket and Ko Samui). The basics of the modeling approach are the same for all basins. For the tourist hotspots, the model resolution is higher to better account for the smaller-scale hydrological features of the landscape. For the five mainland basins, models have been developed with a resolution of 1×1 km². For the three tourist hotspots, the model resolution was increased to 300×300 m².

The wflow_sbm model calculates both land and river runoff. In the model, a distinction is made between land cells and river cells based on the upstream area of the cell. Water can move from the land cells in a downstream direction to other land cells, river cells or directly to the marine environment. For the tourist hotspots, the latter process (direct runoff to the marine environment) is very relevant because there are no, or a limited number of, (big) rivers to transport the water and plastic to the marine environment. An example for Ko Samui is presented in Figure 7.

Since the process depends also on the resolution of the model, an analysis is done to find the optimal resolution of the model. It was found that to represent the important processes that can be modelled with the wflow_sbm model, a resolution of 300×300 m² would suffice for the island models. For the mainland catchments, which are much larger in size, a spatial resolution of 1×1 km² is found to be optimal. To show the difference in detail between different model resolutions, the outlet points of the model to the ocean are shown for three different resolutions in Figure 8. This figure shows that water is not only discharged via the rivers (blue lines), but also directly as surface runoff from the land to the ocean.

The hydrological model also includes a lake and reservoir module, to simulate the effect of reservoir management on the downstream flows. This is highly relevant for the five mainland basins where a total of 16 reservoirs are included in the model schematization. These reservoirs have a large impact on the hydrology and can also trap solid waste. An overview of the reservoirs included in the hydrological model is presented in Figure 9. Only the most important reservoirs had data available to set up, calibrate and validate the model.

For the other reservoirs, assumptions—partly based on global data—are made to simulate reservoir outflow accurately.

Assumptions and Limitations

Before applying the wflow_sbm model for a material flow analysis or when applying the wflow_sbm model for any other purpose, it is important to understand the main assumptions and limitations of the model. See Table 2 for details.

Figure 7.
EXAMPLE OF KO SAMUI SHOWING THE PRINCIPLES OF LAND AND RIVER RUNOFF
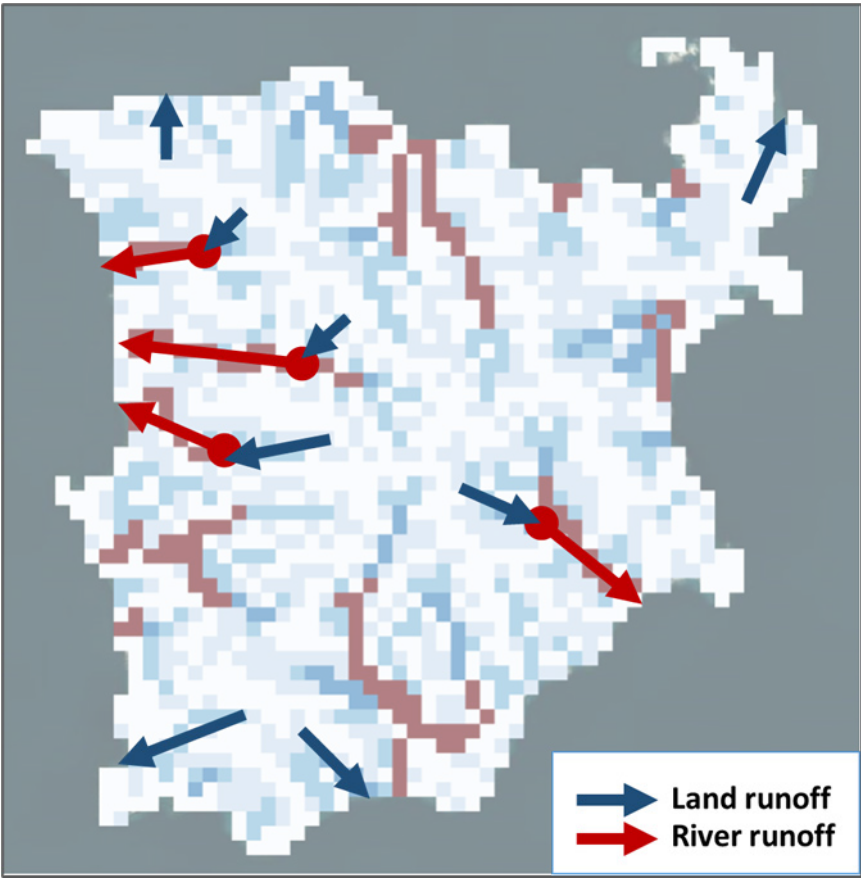
Source: Original figure for this publication.

Figure 8.
OUTLET POINTS OF THE MODEL TO THE OCEAN WITH DIFFERENT RESOLUTIONS. IN BLUE, THE RIVERS ON КО SAMUI
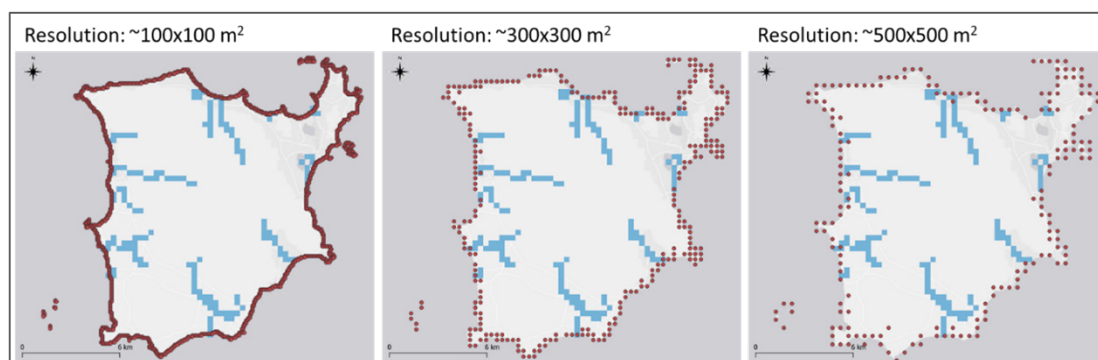
Source: Original figure for this publication.

Figure 9.
OVERVIEW OF THE RESERVOIRS WHICH ARE INCLUDED IN THE HYDROLOGICAL MODEL.[7] IN BLACK, THE CATCHMENT DELINEATION FROM THE DEPARTMENT OF WATER RESOURCES (DWR) IS SHOWN
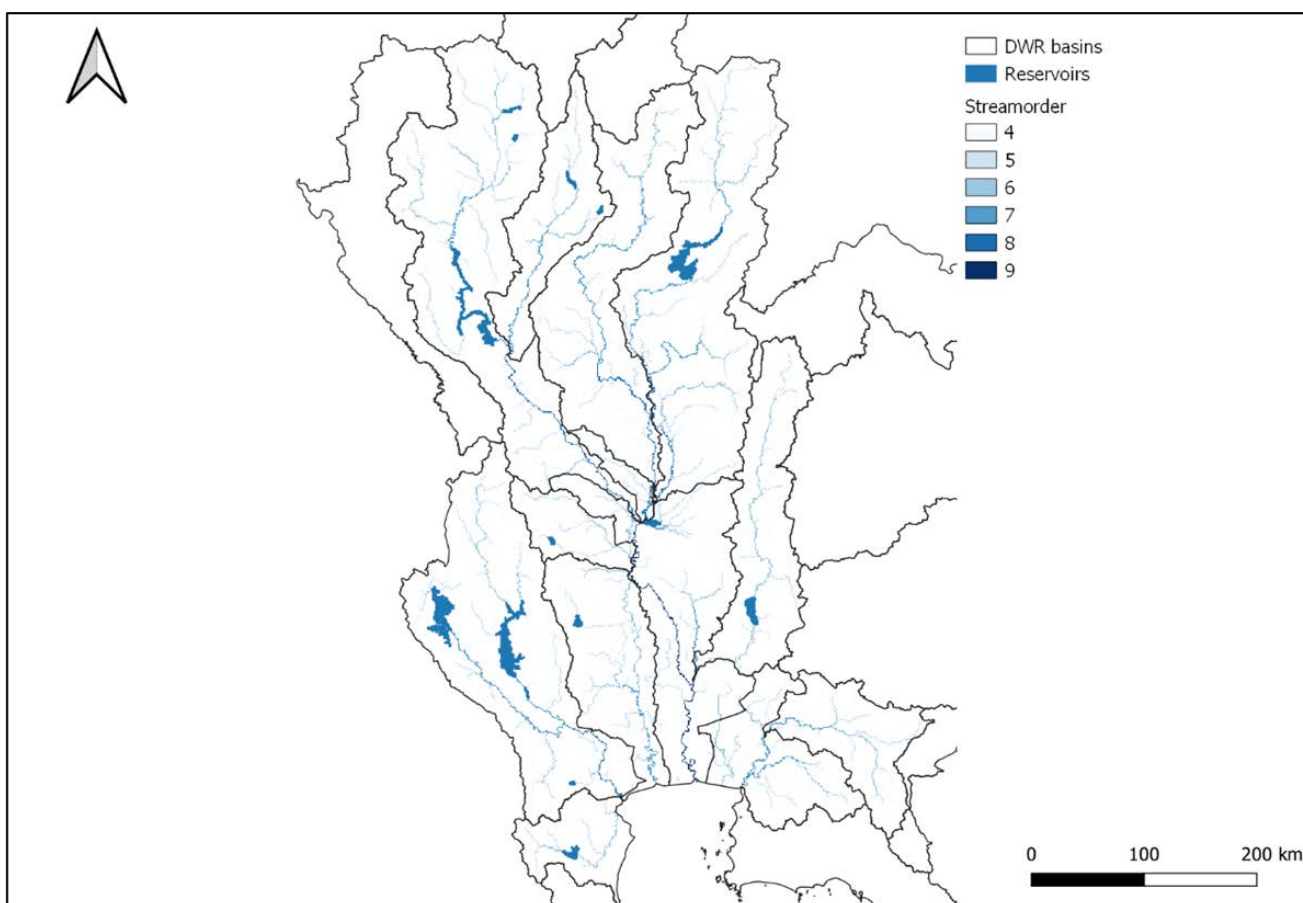
Source: Original figure for this publication.

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7   The stream order is a positive integer value used to indicate the level of branching in a river system. According to the "top down" system devised by Strahler, rivers of the first order are the uppermost tributaries. If two streams of the same order merge, the resulting stream is given a number that is one higher. If two rivers with different stream orders merge, the resulting stream is given the higher of the two numbers.

Table 2.

SUMMARY OF THE ASSUMPTIONS AND LIMITATION IN THE HYDROLOGICAL MODELS AND THE IMPACT ON THE RESULTS

Assumptions made	Expected impact of assumptions
Use of global data sets for model setup After a quick assessment of available local datasets, it was concluded that only datasets for rainfall and reservoirs could be used in the hydrological model. The other underlying datasets were obtained from global datasets specifically established for hydrological assessments of catchments in the absence of local data.	**Digital elevation model (DEM):** The use of a global DEM results in less accurate stream network, especially in the downstream regions of the catchments. The impact on the total catchment area and plastic wash-off is probably low. **Land/soil data:** The land cover data and soil data are coarse. The global data provides less detail, resulting in lower model performance. This can be (partly) fixed by calibration of the model, so the overall impact of this assumption is probably low for the mainland areas. For the coastal zones and small island, the impact is higher as the land cover data for these regions is very inaccurate. In fact, in Ko Samui no urban build-up is seen in the land cover data, resulting in unrealistically low wash-off rates. Improved land cover data could fix this. **Dam/reservoir data:** This information is crucial for correct simulation of the flows in the rivers. Relying on global data alone will heavily affect the results of the hydrological models. A validated local dataset is required to improve the models. This dataset can then be used to change the model parameters such as the target levels (both minimum and maximum) and the release discharge rates for each reservoir. It is assumed that 100% of incoming MPW remains trapped at the dams/reservoirs. Therefore, if certain dams/reservoirs are not included in the model then the discharge may be overestimated. Considering that most dams are located in the upstream catchments and only a small fraction of total MPW is trapped, the effect is likely small.
Limited calibration of the hydrological models	Calibration of the models is the way to improve model performance. The limited calibration results in low performance of the hydrological models in Mae Klong and Phetchaburi catchments (see section 3.3) and for the smaller catchments and islands. Under/overestimation of runoff and/or discharge will result in under/overestimation of MPW wash-off and transport.
Diversions and canals not included in the model	The current model is built on top of the global MERIT Hydro dataset. This dataset is used to derive the (natural) stream network. For the upstream part of the catchments, this works very well, but for the downstream, flat part of the catchments, the derived river network is not accurate and contains errors. This is especially true of the many man-made irrigation and drainage canals that are excluded from the dataset, causing incorrect drainage patterns in this part of the catchment. The wflow_sbm model also works with a one-directional flow that causes some errors in the downstream part of the catchment where many diversions of the flow exist. Large diversion can potentially be added to the model by assuming fixed abstraction rates from the main rivers. This has only been done for the Mae Klong catchment in a very simple manner by adding one abstraction just upstream of the Mae Klong dam. In some catchments, the diverted volumes are normally small. Therefore, on the total plastic wash-off that may reach the marine environment, the impact of this limitation is expected to be low. For specifically Mae Klong and Phetchaburi, the total volume of diverted water is relatively large compared to the total discharge volume of these rivers. In these catchments, the impact of these diversions is potentially large, resulting in under or overestimation of the total runoff and plastic discharge in the model.
Urban drainage not explicitly included in the model[8]	Small-scale (urban) drainage structures (canals, pumps, tunnels) are not included in the model. A detailed analysis of the urban hydrology is therefore not possible using the current models. However, the urban areas are included in the models as areas with reduced infiltration. The general effect of urban areas generating more plastic discharge can therefore be simulated with the current models.

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8   To correctly model the hydrology in the urban environment, a more complex hydrological model should be used. This model is very different from a catchment model like wflow. Such a model should, for example, be able to incorporate two-directional and energy-gradient driven flow (i.e., water can flow in two or more directions) and the model should be able to include typical urban hydrological processes like controlled flow (pumps, gates) and flow via sewer pipes. The urban environment also requires a model to be set up on a (much) higher resolution to account for these small details that strongly determine how water moves through an urban area.
As a simpler workaround, the effect of plastic removal due to urban drainage structures in the current model could potentially be included by adding one or more artificial dams in the wflow model at the locations where the water from the Bangkok areas enter the main rivers. However, this was not included in the model since this requires a thorough analysis on where these fictive barriers would have to be placed, based on the real situation in the Bangkok drainage system. This obviously also needs significant observation data.

2.3.2 Fate and Transport Modeling of Plastics

As shown in Figure 10, the fate and transport modeling comprises two models that apply a spatially and temporally variable numerical modeling approach. The emission model shows the fate and transport of plastics on land from the source of leakage to wash-off into surface water. These calculations are performed on each cell of the model grid and subjected to the time-varying rainfall runoff as calculated by the hydrology model. There is no transport of plastics on land between the model cells. Instead, once plastic mass is washed off to the surface water, it is picked up by the river transport model. This models the fate and transport of plastic as it moves downstream through the surface water network from its source to the final endpoint where it is discharged from the river mouth to the open sea. While on land or in the surface water, plastic is subjected to a number of environmental processes (that is, degradation, burial, retention, etc.) See Box 4 for details. Each of these is described in further detail in the following sections.

Figure 10.
SCHEMATIZED DIAGRAM OF THE APPROACH TO FATE AND TRANSPORT MODELING OF PLASTICS

Source: Original figure for this publication.

Wash-off, Fate and Transport Modeling of Plastic Waste from Land: D-Emissions

D-Emissions is a plugin of the fate and transport modeling software DELWAQ which calculates the transport of plastic from the terrestrial environment to surface waters and the various processes which the plastic is subjected to along the way.

There are three main pathways through which MPW can be released into the environment (Figure 11):

- Direct disposal in water
- Leakage from dumping/fly-tipping
- Leakage from unsanitary landfills (controlled dumps and dumpsites)

Any plastic waste that is not (properly) collected, contained and treated (MPW) can leak into the environment ([1], [2] and [3] from Figure 11). Some MPW is exposed to rainfall and may at some point wash off to a waterway or river [4] or be disposed directly in water [1]. In the environment, MPW is exposed to forces that degrade [6] or bury [7] it. D-Emissions is used to simulate these two processes as first-order removal functions. Plastic waste that is degraded or buried remains in the terrestrial environment and is not remobilized. The remaining fraction of plastic waste is then available to wash-off and can be transported to a waterway, river or lake.

D-Emissions calculates the rate of wash-off for each computational cell based on the infiltration excess calculated by the wflow_sbm model and the source of emission. Wash-off is calculated as a first-order process with a homogenous rate so the rate of plastic wash-off is directly proportional to the rainfall runoff within an upper and lower bound. During dry periods, plastic mass accumulates on the land surface, which is then available to wash-off during the next rainfall event.

Fate and Transport Modeling of Plastic Waste in Rivers: DELWAQ

The routing of surface water is provided by the wflow_sbm model as described in section 2.3.1. This approach applies a DEM to show the water and plastic mass are transported from each cell to its nearest downstream neighbor. Figure 12 shows an example of how this is schematized. The mass flux of plastic that is transported in the surface water is directly proportional to the mass transport flux of water as calculated by the hydrology model.

In a waterway, plastic is subsequently exposed to forces that can further degenerate or trap it (see [8] and [9] in Figure 11), such as settling to the river bottom or becoming caught in vegetation. Plastic waste can be trapped or retained by natural (lakes and vegetation) or artificial (dams, waste traps, etc.)

Figure 11. **CONCEPTUAL FRAMEWORK OF THE FATE AND TRANSPORT OF MPW FROM EMISSION (DIRECT DISPOSAL IN WATER, LEAKAGES FROM FLY-TIPPING AND DUMPSITES) TO SURFACE WATERS INCLUDING THE RETENTION PROCESSES APPLIED ON LAND AND IN RIVERS**
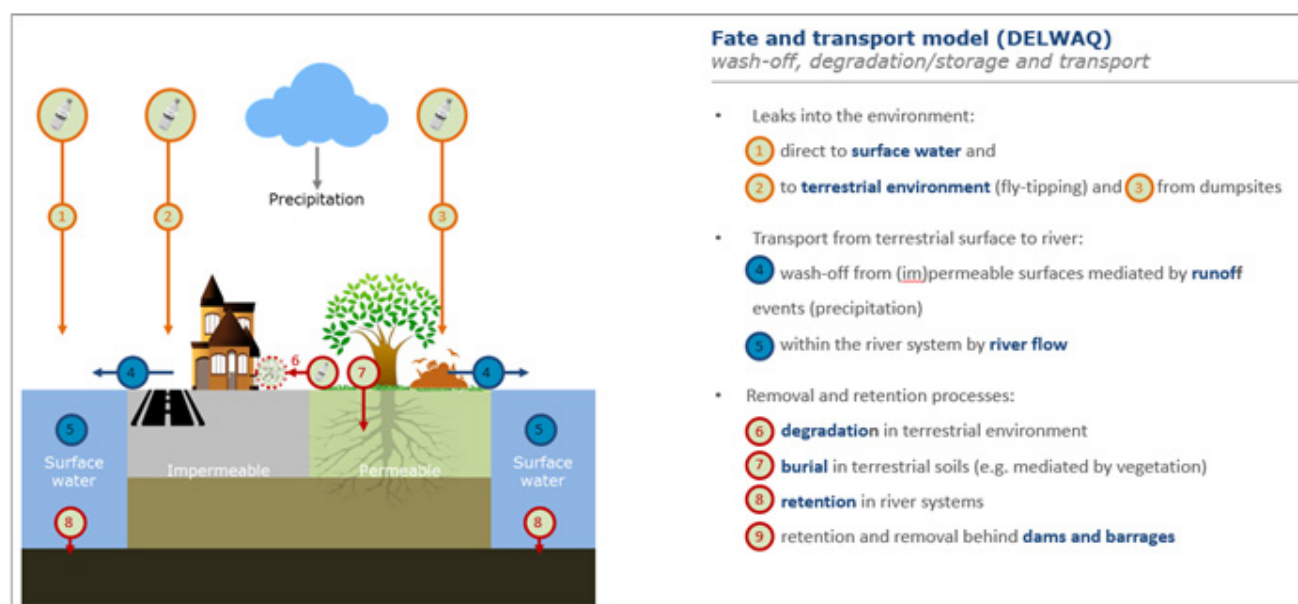
Source: Deltares.

Figure 12.
SCHEMATIC OF FATE AND TRANSPORT MODELING BASED ON WFLOW_SBM GRID. PLASTIC IS WASHED OFF OF THE LAND SURFACE INTO THE SURFACE WATER, WHICH IS THEN CARRIED DOWNSTREAM TO THE NEAREST DOWNSTREAM NEIGHBOR
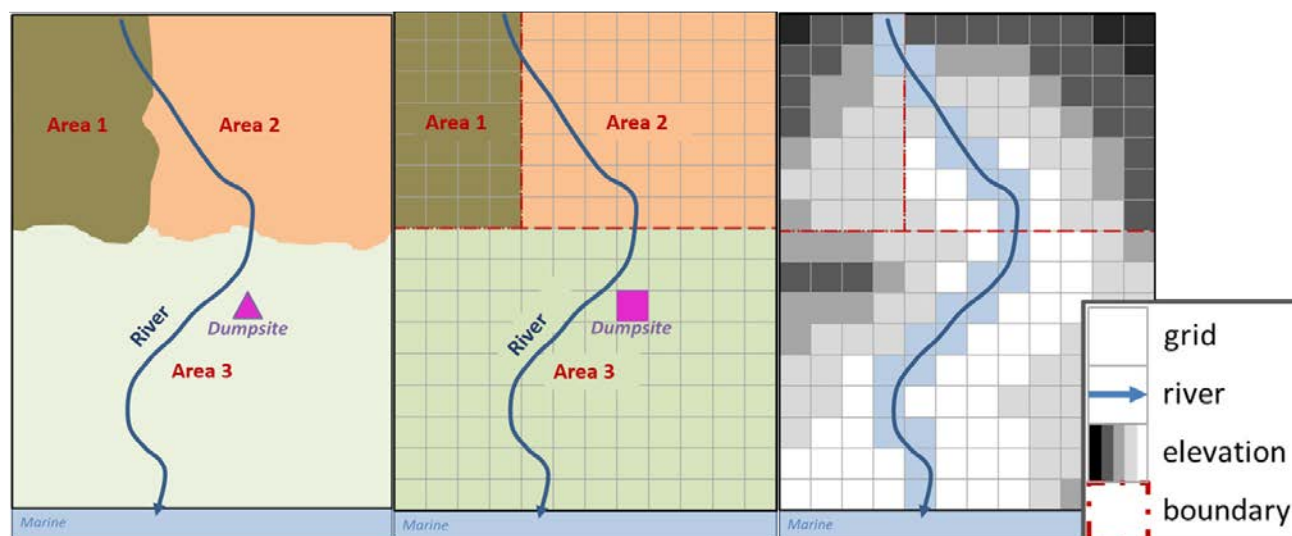
Source: Original figure for this publication.

barriers that may prevent it from reaching the marine environment. Any other fraction of plastic waste is discharged into the marine environment and becomes plastic marine debris.

Although dams and reservoirs have been included in the models as retention points, trash racks have not been incorporated in the models. Trash racks are present in some cities in the urban drainage systems and sometimes in smaller rivers and canals. These structures may capture floating MPW before it reaches the marine environment. However, observations have shown that their retention efficiency varies between different racks and with the season (e.g., during wet season, grid can be lifted to prevent flooding upstream).

Assumptions and Limitations

The MFA methodology used in this study considers all plastic mass as one entity. Therefore, environmental processes based on the size, shape, density and/or polymer type are not modeled explicitly. To avoid overparameterization of the model where these parameters cannot be quantified, the model includes three processes: degradation of material on land, burial in soils and retention within the surface water network. Each of these processes are described as *first-order removal* processes with a constant rate and have been estimated based on literature and expert judgement, while ensuring a complete mass balance. Further details are provided in Table 3.

Photo: Shutterstock / MaeManee.

Table 3.

SUMMARY OF THE ASSUMPTIONS AND LIMITATION IN THE FATE AND TRANSPORT MODELS AND THE IMPACT ON THE RESULTS

Process/ process parameter	Data limitations	Assumptions made	Expected impact of assumptions
Degradation	No data available for degradation of total plastic mass on a catchment scale	Includes all processes which, when, combined describe the physical breakdown of plastic waste into smaller particles that are not modeled (i.e., physical weathering, exposure to UV radiation, mechanical breakdown by road traffic, humans and/or animals).	Calibration of rate constant could only be performed for the five priority catchments. Therefore, we expect the degradation process to be well representative of large catchments in Thailand, but may be overestimated in smaller coastal catchments
		Microplastics resulting from degradation are assumed to be retained on land and are not modeled in the environment. First-order process with rate constant [-d]. This rate constant is determined through a combination of model calibration and expert judgement. Degradation is assumed to be homogenous over area; different rate constants are applied for paved and unpaved area. Single rate constant is determined through calibration of model to measurements of plastic discharge at river mouths of five priority catchments and is applied to all catchments.	The MFA approach means that microplastics are not modeled explicitly in the environment. Therefore, we cannot quantify the extent of influence of microplastics on the total discharge of plastics from rivers to sea, but we assume this to be small relative to larger plastic items.
Burial	No data available for burial of total plastic mass on a catchment scale	Includes all processes which, when combined, describe the capture and retention of plastic so that it is no longer available to wash-off (i.e., burial in the ground, trapping by vegetation and/or infrastructure). First-order process with rate constant [-d]. This rate constant is determined through a combination of model calibration and expert judgement. Burial only occurs over unpaved area. Single rate constant is determined through calibration of model to measurements of plastic discharge at river mouths of five priority catchments and applied to all catchments.	Calibration of rate constant could only be performed for the five priority catchments. Therefore, we expect the burial process to be well representative of large catchments in Thailand, but may be overestimated in smaller coastal catchments. The global datasets used to define land cover are too coarse to adequately represent smaller catchments in Thailand. This can result in an overestimation of burial if built-up areas in a catchment are smaller than the dataset resolution.

Process/ process parameter	Data limitations	Assumptions made	Expected impact of assumptions
Wash-off	No data available for wash-off of macroplastics from land surface on a catchment scale	Wash-off of plastic from land is directly proportional to rainfall runoff. All land surface can be categorized as paved or unpaved. Differing rate constants are applied for both categories. Plastic will begin to wash off after a certain lower threshold of rainfall runoff is reached [mm/d]. There is an upper threshold runoff rate at which all plastic is washed-off [mm/d]. Both the lower threshold and maximum wash-off rates are determined through a combination of model calibration and expert judgement. Single rate constant for both is determined through calibration of model to measurements of plastic discharge at river mouths of five priority catchments and applied to all catchments. Observations were not available to calibrate the threshold values for paved and unpaved areas independently. Both are based on expert judgement.	Results for individual catchments were shown to be sensitive to the ratio of paved to unpaved areas, as the runoff rate for paved areas tends to be much greater than for unpaved areas, resulting in a higher wash-off rate. The global datasets used to define land cover are too coarse to adequately represent smaller catchments in Thailand. For example, no built-up areas in Ko Samui exist in the land cover dataset and the entire island is considered unpaved. This results in very little runoff generated and consequently little wash-off of plastics.
Retention in rivers	Insufficient data available to quantify retention rate constant at a catchment scale	Includes all processes which, when combined, describe the capture and retention of plastic within the surface water. Modeling does not take into account specific river channel features (i.e., bed shape, roughness, vegetation, etc.) Approximated using a standard sedimentation process dependent on flow rate and constant settling velocity applied for inorganic matter [m/d].	There is significant uncertainty in the actual retention of plastic in rivers because channel features could not be modeled at the large spatial scale of this study, and due to the unknown nature of the behavior of plastics in the natural environment. The only way to reduce this uncertainty is to perform detailed measurements in the field to quantify this behavior.
Capture by dams	Estimates of retention at dams at other locations or of other types not available Chao Phraya dam lies upstream of the model boundary, and therefore could not be used directly in this study for model calibration	100% of plastic mass is retained at the dam. All plastic retained at the dam is removed and disposed of in a sanitary landfill facility. All dams are treated equally regardless of size, type or location.	The presence and location of dams are derived from global datasets and may not be representative of the actual water management practices in Thailand. Only large infrastructure with reservoirs at the spatial resolution of the input dataset are included. In the case that 100% of plastic is not actually removed at infrastructure the model may underestimate plastic transport through the rivers. In the case that critical infrastructure is not included, the model may overestimate plastic transport through rivers. It is not yet known how water collection and diversion through urban canals affects plastic transport due to limitations to the spatial refinement of the hydrology model used in this study.

SECTION 3.
STUDY RESULTS

I n this section, the key results from the MPW assessment and the plastic discharge estimates are presented and discussed. Each section is divided into two parts where respectively the results for the high-priority catchments and the tourist hotspots are presented.

3.1 ASSESSMENT OF MPW FROM LAND-BASED SOURCES

In this section, the key results from the MPW assessment in the terrestrial environment are presented and discussed. The assessment is separated into two parts, the first part presents and discusses the results for the high-priority catchments and the second part provides the results for the tourist hotspots. Detailed results segregated by high-priority catchments and tourist hotspots are presented in Appendix C.

3.1.1 High-priority Catchments

This section presents an overview of the SWM and MPW assessment results for the five high-priority catchments that discharge into the upper Gulf of Thailand (Phetchaburi, Mae Klong, Tha Chin, Chao Phraya and Bang Pakong).

Solid Waste and Plastic Waste Generated

The SWM model results indicate that in the high-priority catchments approximately 11,070 kton of municipal waste is generated annually (mid-point estimate). The range for these high-priority catchments is between 9,040 and 14,610 kton of solid waste per year. This is largely correlated with population—the Chao Phraya catchment, with a population of nearly 16 million (four times that of the next largest catchment) generates the highest amount.

Based on data from the PCD, plastic content makes up an average of 17.4 percent of solid waste. The PCD data differentiates plastic content relative to LAO classification and defines plastic content as higher in more densely populated areas (cities and towns) compared to more rural areas. However, on average, each high-priority catchment has a similar plastic content estimate. It is projected that a total of 1,923.3 kton of plastic waste is generated each year in the high-priority catchments.

Final Destination of SWG

Most collected solid waste in the high-priority catchments is either recycled or ends up at sanitary disposal facilities and is well contained. However, 4.4 percent is disposed in controlled dumps, 18.9 percent ends up in formal (open) dumpsites and 0.4 percent is openly burned at formal open burn facilities. Part of the amount disposed in controlled dumps or open dumpsites is assumed available for wash-off and may wash off during rainfall events, flowing into waterways.

Most plastic is formally collected or recycled as part of solid waste, but a significant amount of plastic remains uncollected (mid-range estimate of 11.2 percent, 214.7 kton per year) in high-priority catchments. With the addition of the estimated plastic waste that is disposed of in formal open dumpsites and formal open burning locations and the potential leakages from controlled dumps, a total of 428 kton/

year of MPW is obtained (with a range of 242.9–1,087.0 kton/year).

The source of MPW varies across the catchments (Figure 13). The populous Chao Phraya catchment shows a much higher proportion of MPW from uncollected plastic waste compared to the other catchments that show a higher proportion from open dumping. This is due to a relatively large portion of solid waste that is collected and sent to sanitary disposal facilities or to (un)sanitary disposal facilities *outside of the catchment*. Although the Chao Phraya catchment has the lowest MPW per capita (mid-range estimate of 10.0 kg/capita/year), a large population means that a significant amount of (plastic) waste remains uncollected (mid-range estimate 96.5 kton/year, nearly twice that of the next highest catchment).

Uncollected plastic waste is handled in different ways—disposal on land, disposal in water, openly burned or buried (Figure 14). It is most commonly disposed of via open burning, accounting for 80.7 percent (mid-range estimate) of all uncollected waste in the high-priority catchments. Open burning is practiced by households as it is an easy and relatively cheap way to reduce the volume of uncollected waste.

Exposed MPW (Plastic Waste Available for Wash-off)

Total MPW exposed—the amount of plastic that is available for wash-off—is derived from uncollected plastic waste (directly disposed in water or dumped/fly-tipped), combined with the fraction of collected but mismanaged plastic waste available for wash-off from controlled dumps and formal open dumpsites. It excludes plastic waste that is burned or buried because this is assumed not to be unexposed to rainfall and unavailable for wash-off.

The SWM model estimates that 58.7 percent of MPW that is exposed for wash-off is attributed to handling practices of uncollected waste that may lead to wash-off of leaked plastics into waterways (e.g., fly-tipping and disposal to water). In most catchments, the practice of disposing of uncollected waste on land accounts for the vast majority of this, but in the Chao Phraya catchment, a large portion of exposed MPW originates from disposal directly in water. Most plastic waste available for wash-off from formal disposal facilities originates from open dumpsites (accounting for 38.6 percent of overall MPW available for wash-off).

Figure 13.
MAIN SOURCES AND PATHWAYS FOR MISMANAGED PLASTIC WASTE FOR EACH OF THE CATCHMENTS
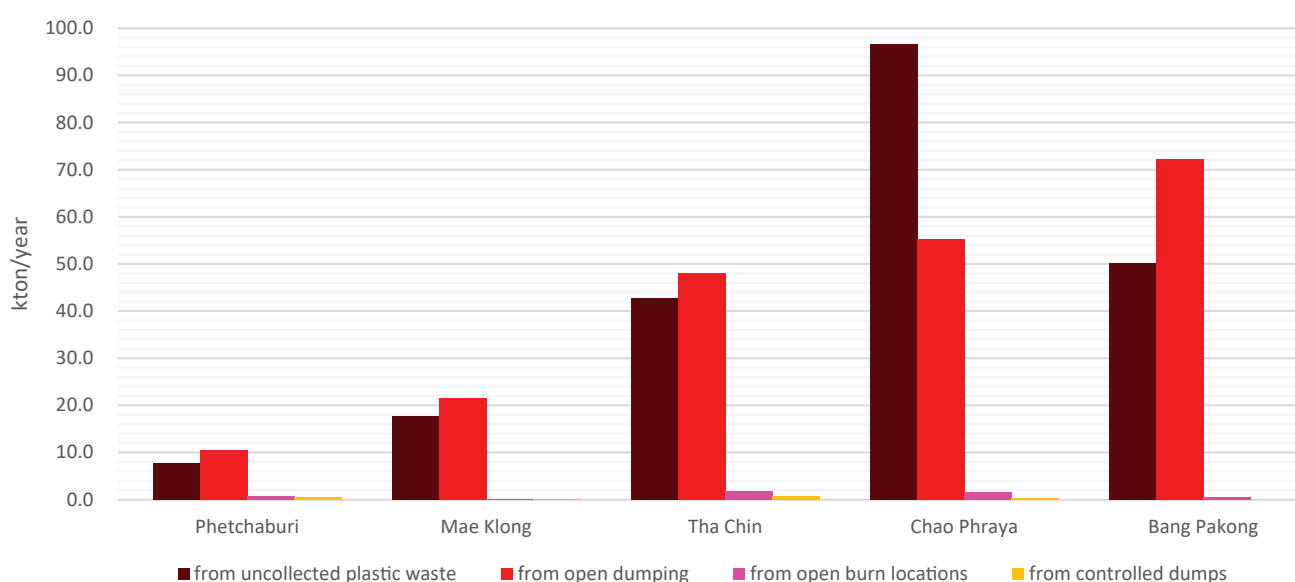
Source: Original calculations for this publication.

Figure 14.
DESTINATION OF UNCOLLECTED PLASTIC WASTE (BASED ON NSO'S SURVEY PERCENTAGE)
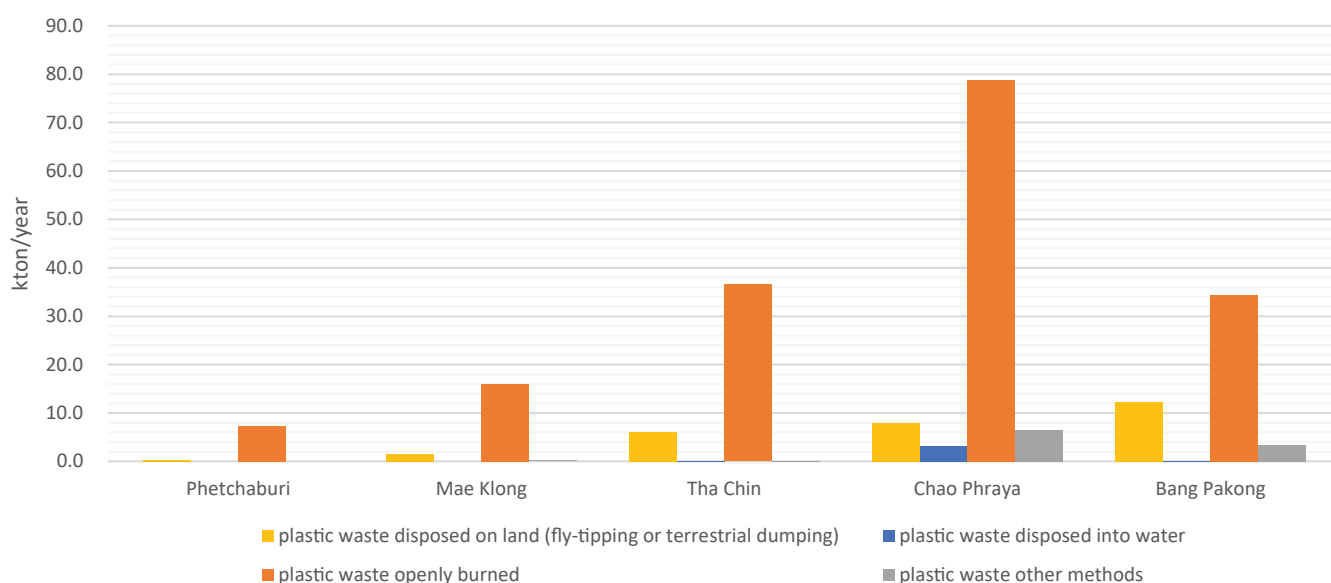
Source: Original calculations for this publication.

There is considerable uncertainty in the results of exposed MPW due to uncertainty in estimating exposed MPW at disposal sites, as well as uncertainty in the amounts of uncollected plastic waste. This uncertainty is highest in the Chao Phraya catchment because of the large population, which is reflected in the large volumes of MPW.

Results Based on LAO Level

In Thailand, SWM is organized through LAOs. To inform policy decisions moving forward, it is important to understand aggregated results at LAO type level. Detailed results and figures at various LAO levels can be found in Appendix D.

Most solid and plastic waste is generated in the BMA. However, despite Bangkok and other cities generating a large amount of waste, most disposal facilities are situated outside cities in smaller subdistricts. This is reflected in the high amounts of solid waste processed and disposed in the subdistrict municipalities and subdistrict administrative organizations (SAOs). It is also here that most unsanitary disposal facilities—that may cause leakages of plastic waste—can be found. The data and model results suggest that a large amount of solid waste is exported from larger urban areas to the rural (sub)districts.

The source of most MPW is in the smaller more rural subdistricts, where the MPW per capita is much higher. But even in the cities, a significant amount of plastic

waste remains uncollected. For uncollected waste, open burning is the most common waste handling practice, but it is much more prevalent in the smaller LAOs than it is in larger towns and cities. The study results indicate that within cities (except for the BMA) disposal of (plastic) waste directly into water is more common than in rural areas (assuming subdistrict municipalities and SAOs are mostly rural municipalities).

Detailed Analysis of Critical Areas Contributing to Exposed MPW

The study results indicate that most MPW is generated in the more rural areas (subdistrict municipality and SAO). It is in these areas that large amounts of (plastic) waste remain uncollected and where most open dumpsites can be found. From these sources, plastic waste may leak into the environment. Figure 15 provides insight into the spatial distribution of exposed MPW in the high-priority catchments.

Table 4 presents the top 10 districts that contribute most to exposed MPW generation in the five high-priority catchments. Together these districts contribute 51.7 percent to the total exposed MPW in the high-priority catchments available from 247 districts. This is a significant contribution and is caused by the fact that these districts contain the largest open dumpsites[9] and, with only a few exceptions,

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9   In the 10 biggest open dumpsites (out of 471 active open dumpsites), 35 percent of solid waste that ends up in open dumpsites is disposed.

Figure 15.
CRITICAL DISTRICTS CONTRIBUTING MOST TO EXPOSED MPW ARE INDICATED WITH RED BOUNDARY
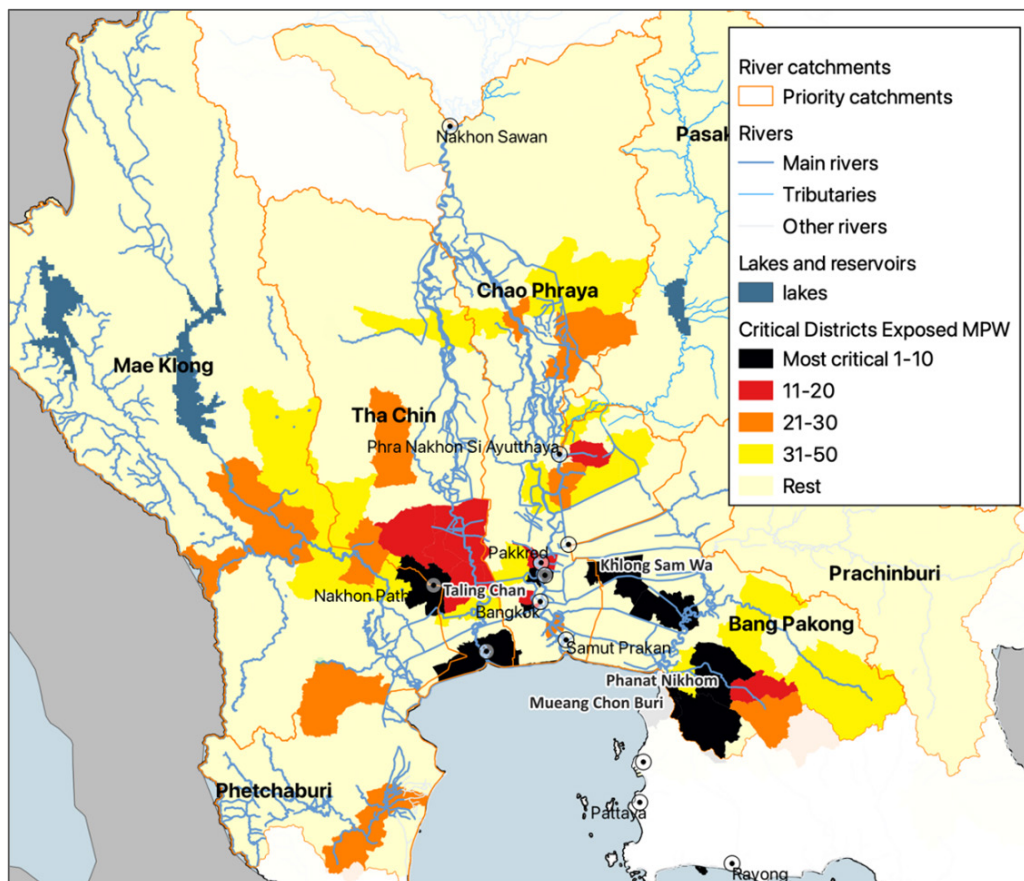
Source: Original calculations for this publication.

collection rates (from formal collection and recycling) are relatively high (around 90.0 percent). This results in high concentrations of MPW in certain districts and specific locations. In other districts the lower collection rates in combination with large populations lead to large amounts of uncollected waste .

Interestingly, the critical districts are all at relatively close distance to the sea. This is partly a reflection of the population distribution but is also a result of the prevailing SWM conditions in the districts; the largest open dumpsites are found at a relatively close distance to Bangkok.

The districts that contribute most to exposed MPW are all situated near Bangkok (Figure 16a-d). In these districts the main source for MPW available for wash-off is uncollected waste.

In Phanat Nikhom (#1) and Mueang Chon Buri (#5), collection rates are low at around 34.8 percent and 51.5 percent respectively, leaving a large portion of SWG uncollected in these districts.

The high relative contribution of Mueang Nonthaburi (#4) to MPW available for wash-off is a result of the large population and hence the large total volume of MPW generated. The collection rate is approximately 75 percent on average, with about 25 percent uncollected. While most uncollected waste is openly burned (80 percent) in Nonthaburi province, a large share of uncollected waste is disposed directly in open water (13 percent) and the remaining part is disposed in the public environment (7 percent).

In Ban Bueng (#2), Mueang Samut Sakhon (#3) and Mueang Chachoengsao (#7), unsanitary disposal facilities are the main source of exposed MPW. The largest open dumpsites can be found in these three districts. These open dumpsites account for just over 25 percent of waste disposed in open dumpsites in the five catchments. Only a small fraction of the plastic that is disposed in these open dumpsites is exposed and available for wash-off. It is suspected that a large amount of solid waste is "imported" from adjacent districts, which would explain the very high rates of MPW per capita.

Table 4.
CRITICAL AREAS THAT CONTRIBUTE MOST TO EXPOSED MPW

ID	District	Exposed MPW (kton/year)			Relative Contribution	Population	Collection Rate	Primary Sources of Exposed MPW		
		High	Mid	Low				Open Dump (kton/year)	Direct to Water (kton/year)	Fly-tipping (kton/year)
TH2006	Phanat Nikhom	7.11	5.18	0.12	9.7%	203,656	34.8%	3.17	-	4.87
TH2002	Ban Bueng	8.93	3.41	1.14	6.4%	155,297	95.4%	31.38	-	0.27
TH7401	Mueang Samut Sakhon	8.65	3.23	1.19	6.0%	559,730	95.8%	30.94	-	-
TH1201	Mueang Nonthaburi	6.28	2.48	0.24	4.6%	656,021	75.0%	-	1.65	0.83
TH2001	Mueang Chon Buri	4.56	2.25	0.09	4.2%	129,241	51.5%	2.42	-	2.01
TH1003	Nong Chok	4.17	2.23	-	4.1%	195,069	63.8%	-	0.09	2.14
TH2401	Mueang Chachoengsao	5.78	2.14	0.78	4.0%	165,316	74.5%	21.43	-	-
TH1022	Phasi Charoen	4.20	2.12	-	4.0%	215,153	68.7%	-	0.08	2.04
TH1019	Taling Chan	3.63	1.80	-	3.3%	192,590	70.4%	-	0.07	1.73
TH1206	Pak Kret	2.14	1.53	0.06	2.8%	363,905	76.9%	-	1.02	0.51

Three districts (#6, #8 and #9) fall within the BMA area. The available SWM data for the BMA area is too coarse (only available at provincial level) to draw specific conclusions about districts. These three districts showing up in the top 10 should be considered more as an indication of a general need to further increase collection within the BMA and to collect detailed data at (sub)district level to improve the SWM database and model, and to better inform improvement efforts.

Looking at the most critical districts in each priority catchment, a wide range of measures are required to address the marine debris problem.

Figure 16a.
SPATIAL DISTRIBUTION OF EXPOSED MPW FROM DUMPING/FLY-TIPPING IN TOP 10 CRITICAL DISTRICTS
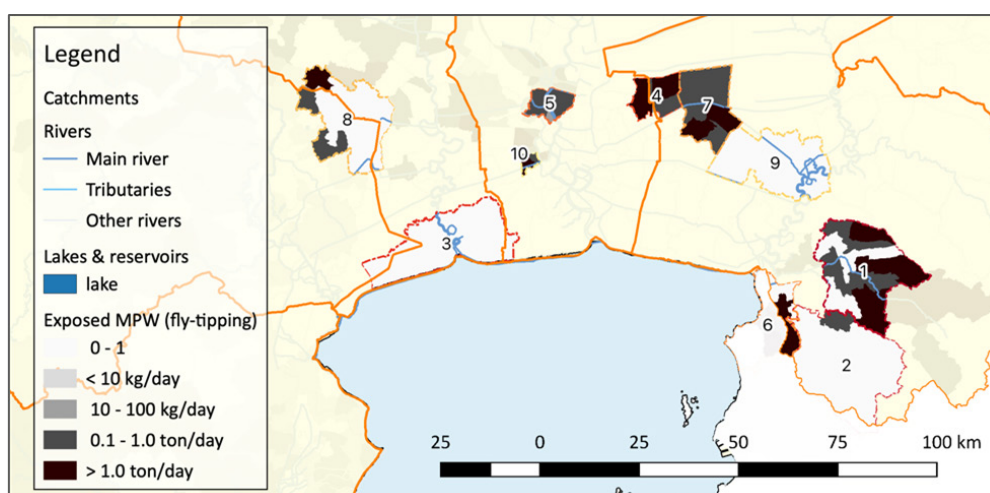
Figure 16b.
SPATIAL DISTRIBUTION OF EXPOSED MPW FROM DIRECT DISPOSAL TO WATER IN TOP 10 CRITICAL DISTRICTS
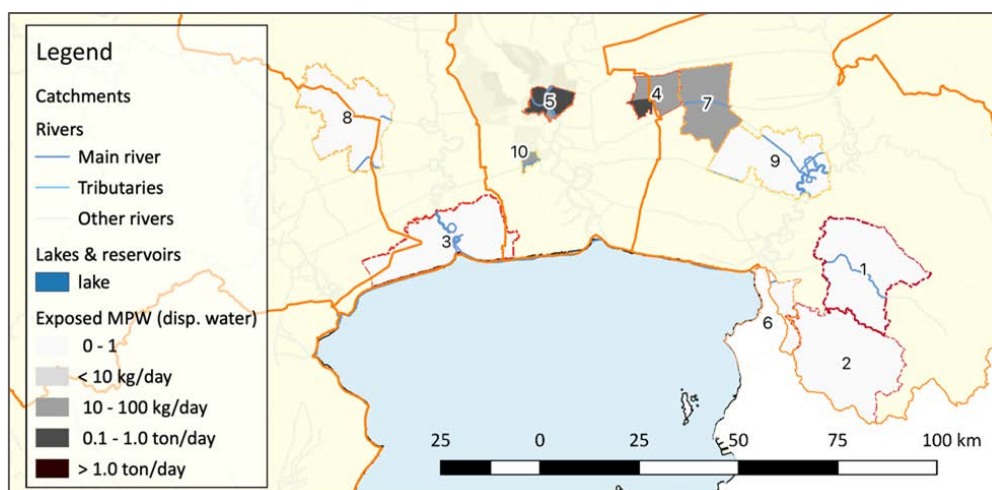
Figure 16c.
SPATIAL DISTRIBUTION OF EXPOSED MPW FROM UNSANITARY LANDFILLS (CONTROLLED DUMPS AND OPEN DUMPSITES) IN TOP 10 CRITICAL DISTRICTS
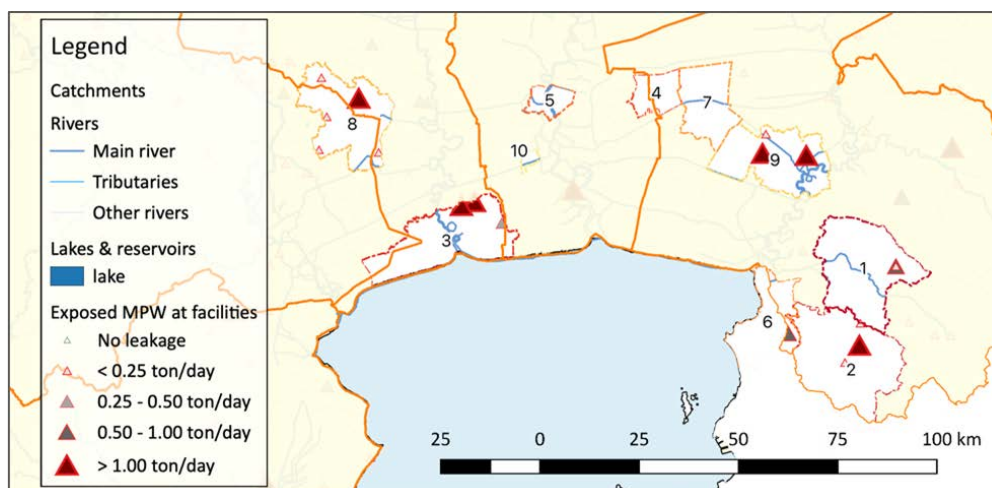
Figure 16d.
LAO TYPES ACROSS TOP 10 CRITICAL DISTRICTS
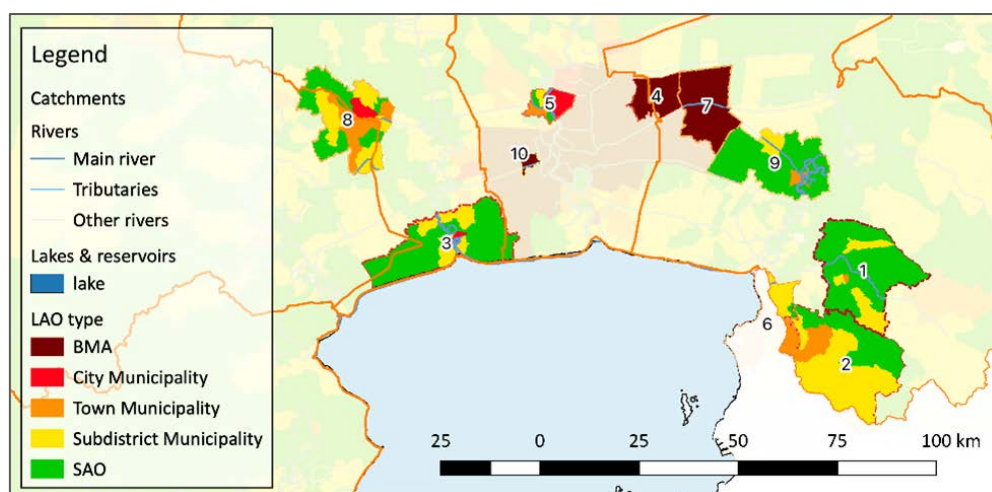
Source: Original calculations for this publication.

Phetchaburi River Catchment

In the top 10 districts that contribute most to exposed MPW in the Phetchaburi River catchment (Table 5), almost all exposed MPW is generated in the more rural districts. Most exposed MPW (84.3 percent) is generated from point sources (unsanitary disposal facilities) and only 15.7 percent from uncollected waste through fly-tipping. To reduce exposed MPW, investments are required to upgrade existing unsanitary disposal facilities and to build new sanitary disposal facilities.

Mae Klong River Catchment

In the top 10 districts that contribute most to exposed MPW in the Mae Klong River catchment (Table 6), almost all exposed MPW is generated in the more rural districts. About 51.4 percent of exposed MPW is generated from point sources (unsanitary disposal facilities) and 48.6 percent from uncollected waste through fly-tipping. To reduce exposed MPW, investments are required to provide proper SWM services in combination with investments to upgrade existing unsanitary disposal facilities and build new sanitary disposal facilities.

Tha Chin River Catchment

In the top 10 districts that contribute most to exposed MPW in the Tha Chin river catchment (Table 7), almost all exposed MPW is generated in the more rural districts. About 45.8 percent of exposed MPW is generated from point sources (unsanitary disposal facilities) and 54.2 percent from uncollected waste through fly-tipping. To reduce exposed MPW, investments are required to provide proper SWM services in combination with investments to upgrade existing unsanitary disposal facilities and to build new sanitary disposal facilities.

Chao Phraya River Catchment

In the top 10 districts that contribute most to exposed MPW in the Chao Phraya River catchment (Table 8), about 20.9 percent of exposed MPW is generated from point sources (unsanitary disposal facilities in the more rural districts) and the rest from uncollected waste in the more urban areas (21.2 percent through direct disposal to water and 57.9 percent through fly-tipping). Investments in the predominantly urban districts should focus on increasing collection rates while investments in more rural districts are required to reduce leakages from unsanitary disposal facilities.

Bang Pakong River Catchment

In the top 10 districts that contribute most to exposed MPW in the Bang Pakong River catchment (Table 9), about 34.2 percent is generated at unsanitary disposal facilities (point sources). Disposal directly into water only accounts for less than 1 percent; the remaining 64.8 percent leaks through fly-tipping. To address the solid waste management issues in this catchment, investments are required in the rural areas to provide proper SWM services and to reduce leakages from unsanitary disposal facilities. In the urban areas collection rates need to be increased and awareness-raising campaigns are required to reduce direct disposal into waterways.

Table 5.
TOP 10 CRITICAL DISTRICTS ACCORDING TO EXPOSED MPW GENERATED IN THE PHETCHABURI RIVER CATCHMENT

| ID | District | Exposed MPW (kton/year) | | | | Relative Contribution | Population | |
| | | Point | Diffuse | | | | Urban | Rural |
		Dry	Dry	Wet	Total			
TH7601	Mueang Phetchaburi	-	0.06	-	0.06	3.5%	12.8%	87.2%
TH7605	Tha Yang	0.65	0.05	-	0.69	39.3%	0.0%	100.0%
TH7606	Ban Lat	0.02	0.04	-	0.07	3.8%	0.0%	100.0%
TH7604	Cha-Am	0.03	0.04	-	0.07	4.0%	48.5%	51.5%
TH7607	Ban Laem	0.10	0.03	-	0.13	7.1%	0.0%	100.0%
TH7608	Kaeng Krachan	0.08	0.02	-	0.11	6.1%	0.0%	100.0%
TH7602	Khao Yoi	0.06	0.02	-	0.08	4.7%	0.0%	100.0%
TH7603	Nong Ya Plong	0.02	0.01	-	0.03	1.8%	0.0%	100.0%
TH7008	Pak Tho	0.52	0.00	-	0.52	29.7%	0.0%	100.0%
TH7010	Ban Kha	-	0.00	-	0.00	0.0%	0.0%	100.0%

Table 6.
TOP 10 CRITICAL DISTRICTS ACCORDING TO EXPOSED MPW GENERATED IN THE MAE KLONG CATCHMENT

| ID | District | Exposed MPW (kton/year) | | | | Relative Contribution | Population | |
| | | Point | Diffuse | | Total | | Urban | Rural |
		Dry	Dry	Wet				
TH7301	Mueang Nakhon Pathom	0.09	0.95	-	1.05	28.2%	32.6%	67.4%
TH7103	Bo Phloi	0.06	0.10	-	0.16	4.2%	0.0%	100.0%
TH7101	Mueang Kanchanaburi	0.68	0.09	-	0.77	20.7%	33.3%	66.7%
TH7108	Sangkhla Buri	0.08	0.07	-	0.15	4.0%	0.0%	100.0%
TH7112	Nong Prue	0.02	0.06	-	0.08	2.3%	0.0%	100.0%
TH7105	Tha Maka	0.16	0.06	-	0.22	5.9%	2.6%	97.4%
TH7102	Sai Yok	0.10	0.04	-	0.14	3.8%	0.0%	100.0%
TH7106	Tha Muang	0.19	0.04	-	0.23	6.3%	9.3%	90.7%
TH7107	Thong Pha Phum	0.11	0.04	-	0.15	4.0%	0.0%	100.0%
TH7111	Dan Makham Tia	0.05	0.02	-	0.07	1.8%	0.0%	100.0%

Table 7.
TOP 10 CRITICAL DISTRICTS ACCORDING TO EXPOSED MPW GENERATED IN THE THA CHIN CATCHMENT

| ID | District | Exposed MPW (kton/year) | | | | Relative Contribution | Population | |
| | | Point | Diffuse | | Total | | Urban | Rural |
		Dry	Dry	Wet				
TH7401	Mueang Samut Sakhon	3.23	-	-	3.23	28.6%	5.3%	94.7%
TH7305	Bang Len	0.01	1.38	-	1.39	10.6%	0.0%	100.0%
TH7301	Mueang Nakhon Pathom	0.45	0.71	-	1.16	10.3%	32.6%	67.4%
TH7302	Kamphaeng Saen	-	1.13	-	1.13	10.0%	0.0%	100.0%
TH7304	Don Tum	0.10	0.85	-	0.95	8.4%	0.0%	100.0%
TH7303	Nakhon Chai Si	0.21	0.72	-	0.93	8.2%	0.0%	100.0%
TH7307	Phutthamonthon	-	0.80	-	0.80	7.1%	0.0%	100.0%
TH7209	U Thong	0.55	-	-	0.55	4.8%	0.0%	100.0%
TH7306	Sam Phran	-	0.22	-	0.22	1.9%	24.5%	75.5%
TH7202	Doem Bang Nang Buat	0.19	-	-	0.19	1.7%	0.0%	100.0%

Table 8.
TOP 10 CRITICAL DISTRICTS ACCORDING TO EXPOSED MPW GENERATED IN THE CHAO PHRAYA CATCHMENT

| ID | District | Exposed MPW (kton/year) | | | Total | Relative Contribution | Population | |
| | | Point | Diffuse | | | | | |
		Dry	Dry	Wet			Urban	Rural
TH1201	Mueang Nonthaburi	-	0.83	1.65	2.48	14.8%	79.7%	20.3%
TH1022	Phasi Charoen	-	2.04	0.08	2.12	12.7%	100.0%	0.0%
TH1019	Taling Chan	-	1.73	0.07	1.80	10.7%	100.0%	0.0%
TH1046	Khlong Sam Wa	-	1.46	0.06	1.52	9.1%	100.0%	0.0%
TH1206	Pak Kret	-	0.41	0.83	1.24	7.4%	64.1%	35.9%
TH1016	Bangkok Yai	-	0.96	0.04	1.00	6.0%	100.0%	0.0%
TH1414	Uthai	0.87	-	-	0.87	5.2%	0.0%	100.0%
TH1104	Phra Pradaeng	0.72	-	-	0.72	4.3%	79.3%	20.7%
TH1601	Mueang Lop Buri	0.63	0.03	-	0.66	3.9%	21.6%	78.4%
TH1406	Bang Pa-In	0.46	-	-	0.46	2.8%	7.5%	92.5%

Table 9.
TOP 10 CRITICAL DISTRICTS ACCORDING TO EXPOSED MPW GENERATED IN THE BANG PAKONG CATCHMENT

| ID | District | Exposed MPW (kton/year) | | | Total | Relative Contribution | Population | |
| | | Point | Diffuse | | | | | |
		Dry	Dry	Wet			Urban	Rural
TH2006	Phanat Nikhom	0.32	4.63	-	4.95	25.5%	3.2%	96.8%
TH2002	Ban Bueng	3.14	0.27	-	3.41	17.6%	18.8%	81.2%
TH2001	Mueang Chon Buri	0.24	2.01	-	2.25	11.6%	15.4%	84.6%
TH1003	Nong Chok	-	2.14	0.09	2.23	11.5%	100.0%	0.0%
TH2401	Mueang Chachoengsao	2.14	-	-	2.14	11.0%	15.3%	84.7%
TH2011	Ko Chan	-	1.33	-	1.33	6.9%	45.4%	54.6%
TH1046	Khlong Sam Wa	-	1.03	0.04	1.07	5.5%	100.0%	0.0%
TH2010	Bo Thong	0.12	0.36	-	0.48	2.5%	0.0%	100.0%
TH2406	Phanom Sarakham	0.37	-	-	0.37	1.9%	0.0%	100.0%
TH2005	Phan Thong	0.00	0.28	-	0.28	1.5%	0.0%	100.0%

3.1.2 Tourist Hotspots

This section presents an overview of the SWM and MPW assessment results for three tourist hotspots (Phuket, Krabi and Ko Samui).

Solid Waste and Plastic Waste Generated

The generation of solid and plastic waste in tourist areas varies between the resident and tourist populations. However, there is no data available in the tourist hotspots to differentiate the origin of solid waste or the plastic content of solid waste.

The SWM model results indicate that in the tourist hotspots, approximately 381.9 kton of MSW is generated annually (mid-point estimate). Based on data from the PCD, which does not differentiate for tourist areas, plastic content in solid waste is similar to the high-priority catchments with an average of 17.2 percent. It is estimated that in the tourist hotspots, a total of 65.8 kton of plastic waste is generated annually.

Final Destination of SWG

An estimated 86.2 kton of plastic waste finds its final destination in the tourist hotspots and the additional 19.8 kton likely originates from adjacent (sub)districts. Most plastic is formally collected or recycled and only 10.5 percent of plastic waste that arrives in the area remains uncollected. The model results indicate that in Ko Samui, no (plastic) waste remains uncollected. This is likely unrealistic but is a result of the limited district-specific data available.

According to the 2018 data, all formally collected waste in Phuket flows to the sanitary disposal facility on the island, compared to 85.2 percent in Krabi and a negligible amount in Ko Samui where most waste ends up in an open dumpsite. However, there are ongoing developments that are not yet reflected in the available data. It is known that in Phuket, the landfill capacity is almost reached and the city government is actively looking for alternatives. Similarly, in Ko Samui, alternatives are under development and currently (2021) all waste is wrapped in the island and transported to the mainland for final disposal with no waste disposed at the old open dumpsite.

Adding the estimated amount of plastic waste that is disposed of in formal open dumpsites (11.1 kton/year) to the estimated 6.9 kton plastic (10.5 percent) that remains uncollected in the tourist hotspots, a total mid-range estimate of 16.8 kton/year of MPW is obtained. However, as noted above, the Ko Samui open dumpsite is not currently operational. Removing this dumpsite from the estimates, the total is approximately
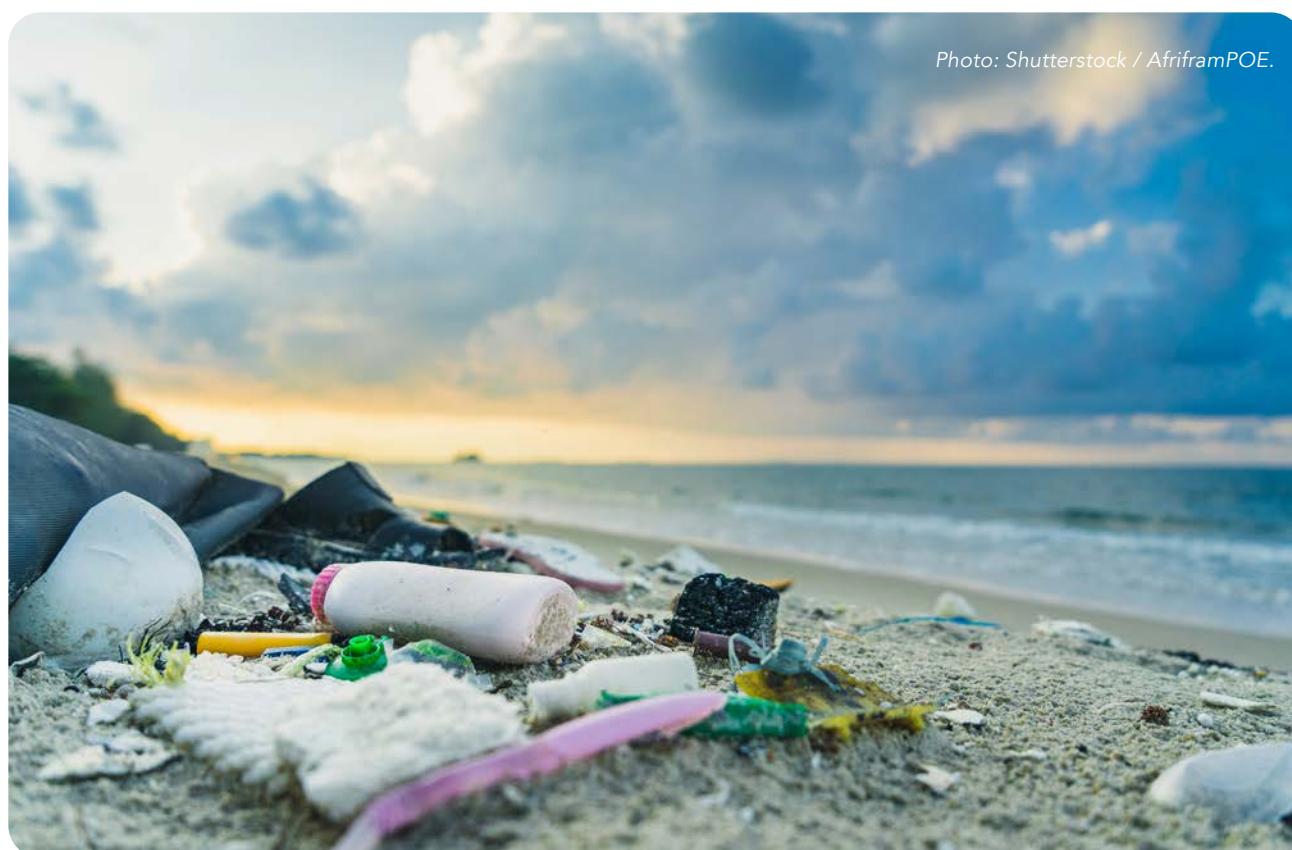
Photo: Shutterstock / AfriframPOE.

Figure 17.
MAIN SOURCES AND PATHWAYS FOR MPW FOR EACH OF THE CATCHMENTS
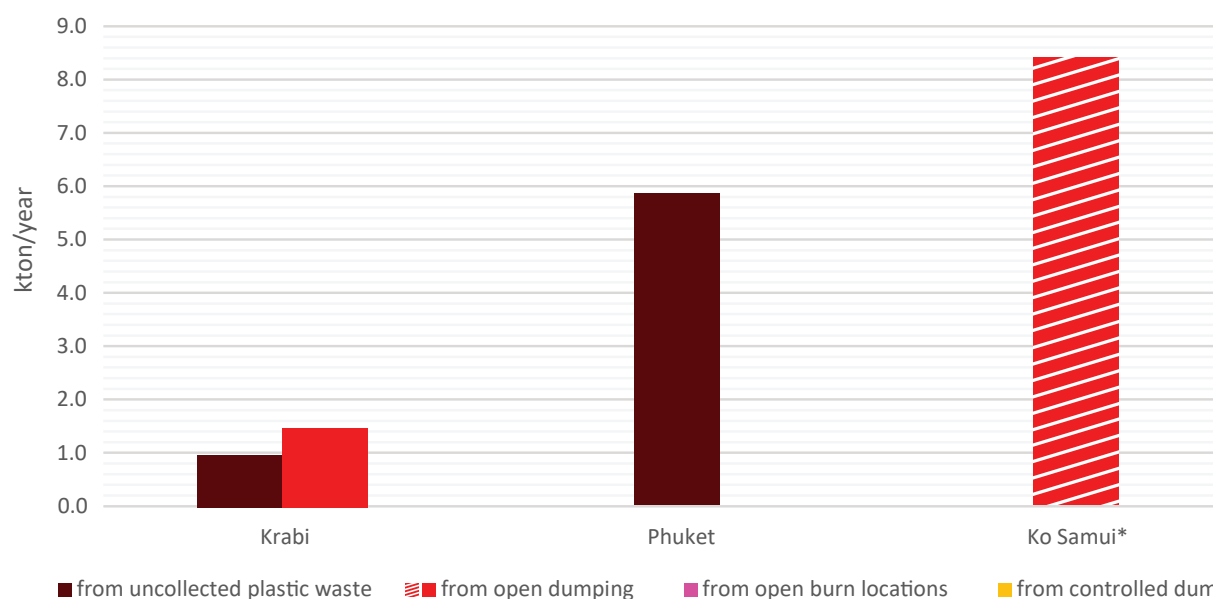
* Note that currently in Ko Samui, all collected waste is wrapped and transported to the mainland for final disposal and is no longer disposed at the open dumpsite.

Source: Original calculations for this publication.

10 kton/year of MPW. In Phuket, this amount is derived from uncollected waste but in Krabi, MPW is evenly divided between uncollected waste and disposal at open dumpsites. Figure 17 shows the source distribution of MPW in the three tourist hotspots.[10]

Uncollected plastic waste in the tourist hotspots is primarily either handled via disposal on land or open burning. It is estimated that about 9.7 percent of the total amount of plastic waste generated and 91.9 percent of uncollected plastic waste is openly burned. Households continue to practice open burning because it is an easy and relatively cheap way to reduce the volume of uncollected waste.

Exposed MPW (Plastic Waste Available for Wash-off)

Total MPW exposed—the amount of plastic waste that is available for wash-off—is derived from uncollected waste (disposed in the environment/fly-tipping) combined with the fraction of collected, but mismanaged, plastic waste available for wash-off from formal open dumpsites. Considering the data limitations for Ko Samui[11], the SWM model provides

a mid-point estimate of exposed MPW for the tourist hotspots as 0.7 kton/year, with 0.5 kton/year attributed to handling practices of uncollected waste and 0.2 kton/year from open dumpsites in Krabi province.

As with the high-priority catchment areas, there is considerable uncertainty in the amount of exposed MPW in the tourist hotspots. This uncertainty is partly a result of the uncertainty in exposed MPW at unsanitary disposal facilities (only in Krabi and Ko Samui), but is also caused by the uncertainty in the amount of uncollected (plastic) waste.

Detailed Analysis of Critical Areas Contributing to Exposed MPW

The study results indicate that exposed MPW is leaked into the environment primarily as point source in the city and as mostly diffuse sources (from uncollected waste) in the more rural LAOs. Figures 18a-c provide insight into the spatial distribution of exposed MPW in the tourist hotspots.

In Table 10, the contribution of the districts to exposed MPW generation in the tourist hotspots are presented. Three districts—Ko Samui, Mueang Phuket, and Khao Phanom—contribute nearly 90 percent to exposed MPW.

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10   Note that currently in Ko Samui, all collected waste is wrapped and transported to the mainland for final disposal and is no longer disposed at the open dumpsite.

11   Note that currently in Ko Samui, all collected waste is wrapped and transported to the mainland for final disposal. Based on the available data (which include the presence of an open dumpsite on the island), the model indicates that no waste remains uncollected.

Figure 18a.
SPATIAL DISTRIBUTION OF EXPOSED MPW FROM DUMPING/FLY-TIPPING IN TOURIST HOTSPOTS
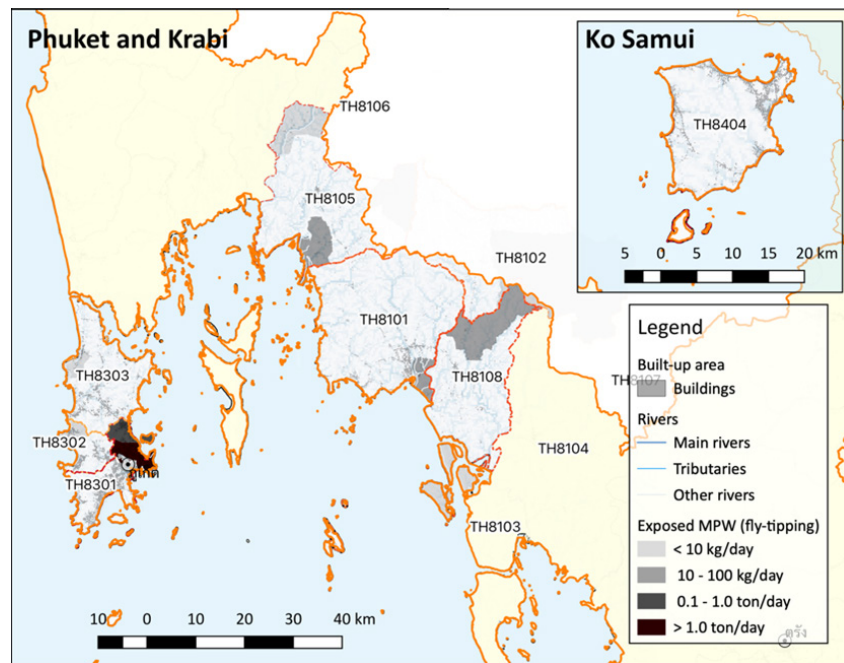
Figure 18b.
SPATIAL DISTRIBUTION OF EXPOSED MPW FROM UNSANITARY LANDFILLS (CONTROLLED DUMPS AND OPEN DUMPSITES) IN TOURIST HOTSPOTS
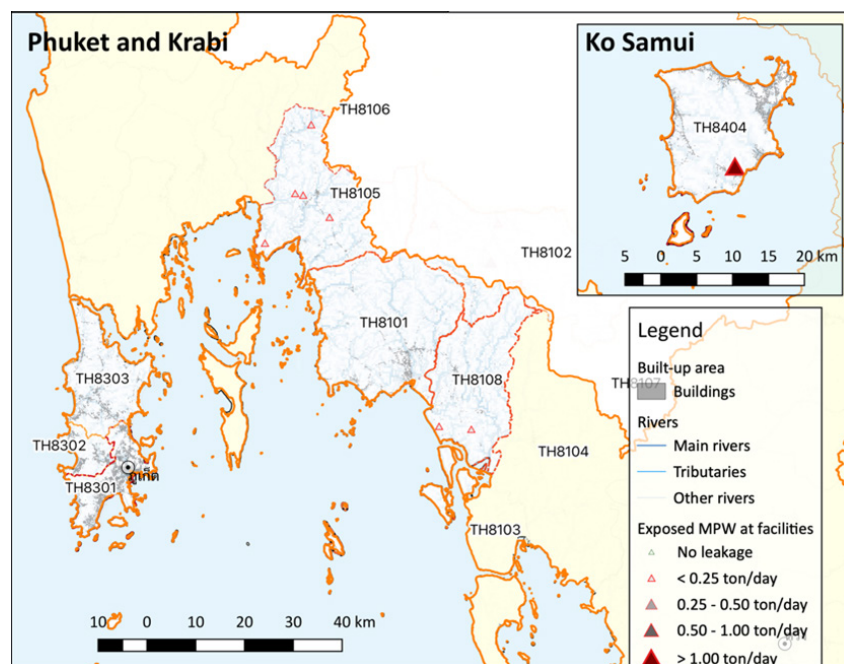
Figure 18c. **LAO TYPES ACROSS TOURIST HOTSPOTS**
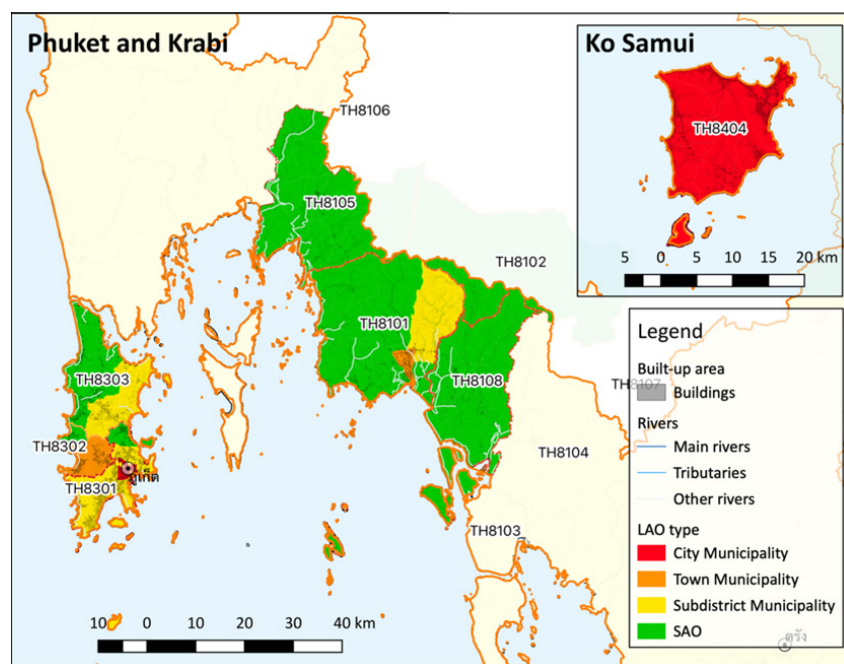
Source: Original calculations for this publication.

Table 10.
RELATIVE CONTRIBUTION OF DISTRICTS TO EXPOSED MPW IN THE THREE TOURIST HOTSPOTS[12]

Rank	ID	District	Exposed MPW (kton/year)			Relative Contribution to Total Exposed MPW	Population	SWG/cap	Collection Rate	Primary Sources of Exposed MPW		
			High	Med	Low					Open Dump (kton/year)	Direct to Water (kton/year)	Fly-tipping (kton/year)
3	TH8105	Ao Luek	0.36	0.11	0.04	7.5%	39,648	1.06	87.8%	1.07	-	0.01
4	TH8108	Nuea Khlong	0.20	0.05	0.02	3.5%	48,674	1.12	88.0%	0.45	-	0.01
5	TH8101	Mueang Krabi	0.22	0.01	0.00	0.3%	82,795	1.52	97.2%	-	-	0.01
6	TH8102	Khao Phanom	0.02	0.00	0.00	0.1%	7,650	1.23	92.4%	-	-	0.00
7	TH8303	Thalang	0.23	0.00	-	0.0%	178,668	0.80	100.0%	-	-	0.00
2	TH8301	Mueang Phuket	0.84	0.52	0.00	34.1%	413,375	1.14	80.0%	-	-	0.52
8	TH8302	Kathu	0.05	0.00	0.00	0.0%	111,575	1.09	100.0%	-	-	0.00
1	TH8404	Ko Samui	3.23	0.84	0.30	54.5%	42,023	1.89	100.0%	8.35	-	-

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12 Note that currently in Ko Samui, all collected waste is wrapped and transported to the mainland for final disposal. Based on the available data (which include the presence of an open dumpsite on the island), the model indicates that no waste remains uncollected.

3.2 ESTIMATED PLASTIC DISCHARGES FROM RIVERS AND COASTAL AREAS

MPW that is disposed of improperly in the dry terrestrial environment can be exposed to wash-off. However, it may take some time to be mobilized by rainfall runoff into streams, rivers or lakes. During this time, MPW is exposed to natural processes that may bury or fragment plastics and prevent a fraction of MPW from being washed off. MPW that ends up in a stream, river or lake is transported downstream and may end up in the marine environment, unless prevented from doing so by natural processes or anthropogenic in-frastructures. The longer MPW remains in a river, with long travel times in general associated with larger catchments and inland communities, the more MPW is weathered and fragmented by natural processes and the more these fragments will be retained (e.g., in river sediments). Fate and transport modeling is used to approximate these processes.

This section presents the results from the fate and transportation modeling of exposed MPW for the high-priority catchments and the tourist hotspots. First, the results of actual wash-off of exposed MPW in the dry terrestrial environment are presented. Second, the results of the transport and fate modeling of MPW in the rivers are presented, followed by a presentation of estimated MPW discharges into the marine environment and a brief discussion on the seasonality of MPW discharges into the marine environment.

There is low confidence in the hydrological modeling for the Mae Klong catchment and the tourist hotspot areas. Therefore, the fate and transport results for these should be interpreted with caution. See further detail in section 3.3. **Please note, the results for the Mae Klong are not considered when presenting totals or averages for the high-priority catchments in this section.**

3.2.1 Estimated MPW Discharges from High-priority Catchments

Wash-off of MPW from Land into Waterways

The fate and transport model indicates that a mid-range estimate of 63 percent (27.7 kton/year) of exposed MPW remains in the terrestrial environment (e.g., buried by natural processes), while the rest (37 percent) washes off to streams, rivers or lakes (16.3 kton/year).

Incorporating MPW that is directly disposed in water and does not remain in the terrestrial environment, increases the average percentage of plastic waste that ends up in a waterway to 41.3 percent (19.5 kton/year) of the total MPW that is both available for wash-off and directly disposed in water.

As seen in Figure 19, most MPW is from the highly populated catchments of the Tha Chin, Chao Phraya, and Bang Pakong Rivers. In the Phetchaburi Bang Pakong catchments, a large fraction of exposed MPW remains in the terrestrial environment (about 80–90 percent). In these catchments, most exposed MPW leaks into the environment as diffuse source and in the upstream reaches of the catchment where subdistricts tend to be large and more rural.

Transport and Fate of MPW in Rivers

Overall, across the four high-priority catchments (excluding Mae Klong), 46.9 percent of MPW that ends up in a river is discharged into the marine environment. The remaining MPW is retained in the riverine system (51.9 percent across the four catchments) or captured behind dams (1.2 percent across the catchments) (Figure 20). The Tha Chin River has the highest plastic discharge (mid-range estimate of 4.01 kton/year) following by the Chao Phraya River (3.45 kton/year) and the Bang Pakong River (1.80 kton/year) (Figure 21).

The modeled MPW discharge estimates for the rivers (most importantly the Chao Phraya River, which runs through Bangkok) have not been corrected for plastic waste that is retained and removed through waste racks and (in)formal removal activities (mostly limited to working hours). In Bangkok, for example, a significant amount of debris is removed from the river through regular cleaning operations and a large amount of waste accumulates in the urban drainage system and retention ponds (where it may increase urban flood hazards) and may, from time-to-time, be retrieved. However, the activities are not sufficiently continuous and predictable to account for in the models. In addition, during certain periods and events, the cleaning activities may be suspended and waste racks/gates may be opened to prevent upstream flooding. Therefore, all waste that is carried in the upstream system runs through. Although a significant amount of waste may be retrieved from the system via cleaning activities and waste racks, this may only be the tip of the 'waste-berg'.

Figure 19.

FATE OF EXPOSED MPW FROM LAND-BASED SOURCES FOR THE HIGH-PRIORITY CATCHMENTS IN THAILAND
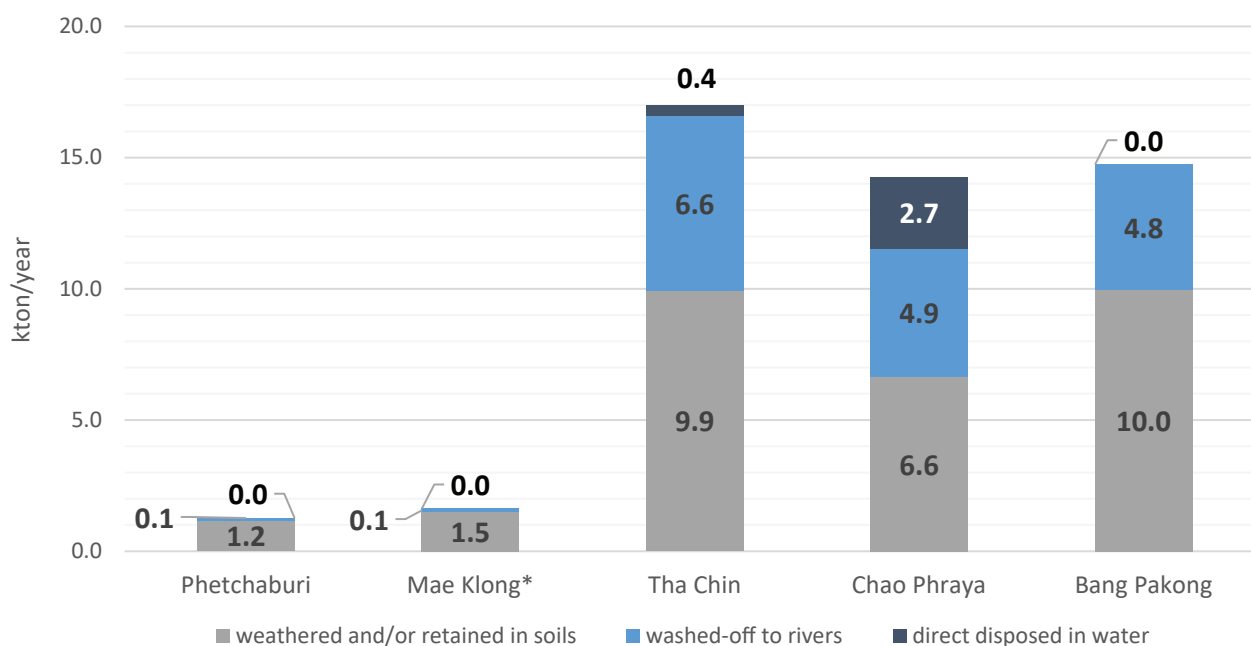
weathered and/or retained in soils · *washed-off to rivers* · *direct disposed in water*

*Results for Mae Klong River have low confidence and are not included in the presented figures in the text.

Source: Original calculations for this publication.

Figure 20.

FATE OF MPW TRANSPORTED IN THE MAIN RIVERS OF THE FIVE HIGH-PRIORITY CATCHMENTS
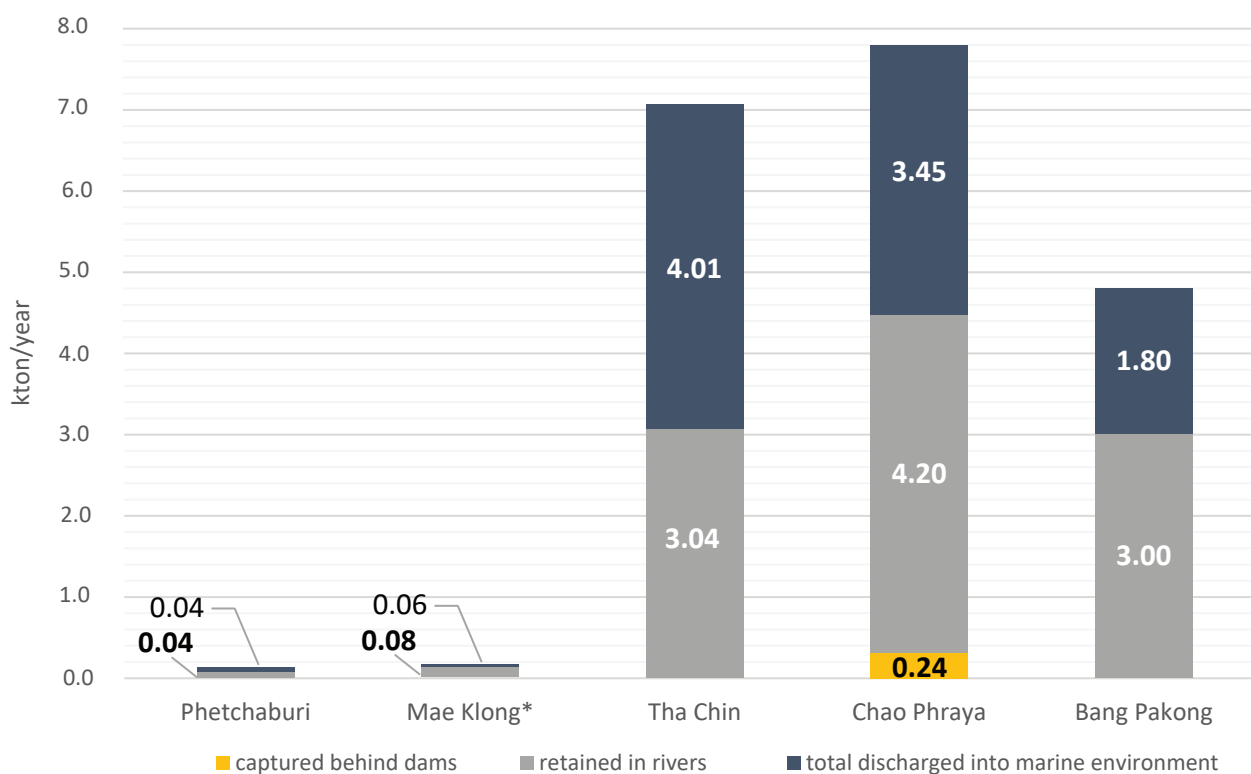
captured behind dams · *retained in rivers* · *total discharged into marine environment*

*Results for Mae Klong River have low confidence and are not included in the presented figures in the text.

Source: Original calculations for this publication.

Figure 21.

SPATIAL DISTRIBUTION OF EXPOSED MPW (GREY SHADES) AND THE RESULTING MID-POINT ESTIMATES OF MPW DISCHARGED INTO THE MARINE ENVIRONMENT (BLUE CIRCLES) FROM RIVER MOUTHS AND COASTAL AREAS
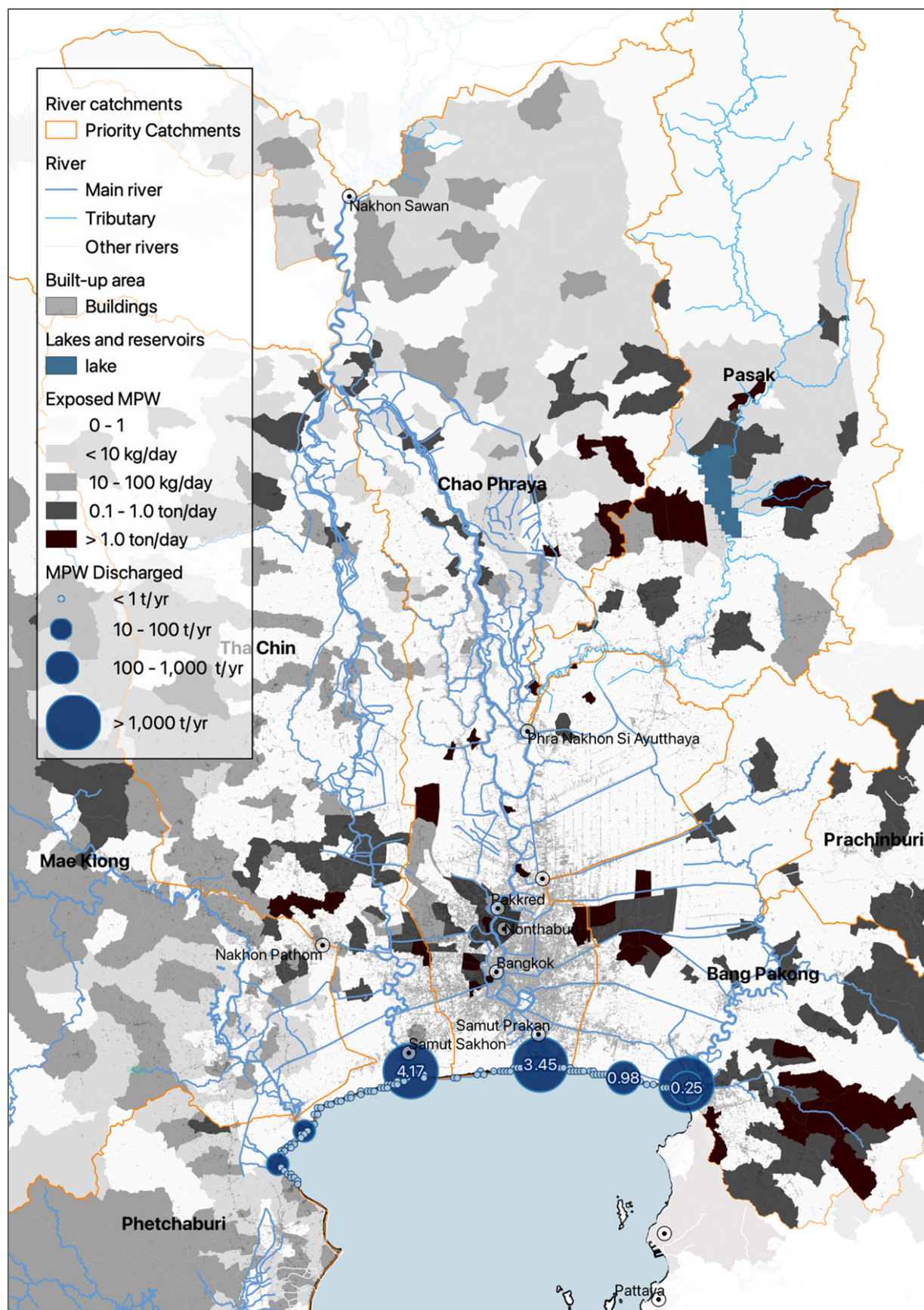
Source: Original calculations for this publication.

Seasonal and Daily Variations of Plastic Discharges from Rivers

To assess seasonal variations of plastic discharges, the complete time series of the fate and transport model as well as the complete time series of the hydrological model are analyzed. The simulated period for the hydrological model covers the period from January 2010 to December 2018 and is based on observed (through remote sensing) daily rainfall distribution. This provides an accurate representation of hydrological conditions for every day in the simulated period. The SWM model is based on reported data considered representative for the year 2018 only and does not contain information on any variability during the year. The model also does not include population growth, economic development and changing behaviors. While this is a limitation of the model, the study does not aim to construct a historical time series to estimate historical discharges of plastics into the marine environment. Rather, by using a static flux of exposed MPW, it is possible to assess the effect of hydrology on the expected discharge of MPW into the marine environment. This makes evaluation of policy options and verification of the actual effects through observations easier. For example, field observations may show no change or an increase in plastic discharges after implementation of policy measures which could suggest that measures are not working, while the increase may, in reality, be caused by hydrological variations.

Model results show strong seasonal variations with higher discharges associated with the rainy season and lower average discharges with the dry season (e.g., the Tha Chin River in Figure 22). In Thailand, the rainy season starts around June and lasts until October, and this is also clearly visible in the modeled MPW discharges.

However, even during the dry season, modeled high discharges of MPW may be expected after brief rainfall events (e.g., the early 2012 rainfall event in the Chao Phraya River, Figure 23). This behavior has also been observed in other catchments where a short rainfall event after a dry spell can mobilize a large amount of accumulated exposed MPW in the catchment. This will then be washed off, transported downstream and discharged into the marine environment.

Overall, the model results indicate large daily variations in MPW discharge. This should be taken into consideration when monitoring rivers and elsewhere. These large daily variations have been observed in field measurements elsewhere (World Bank 2021);

Figure 22.
MODELED TIME SERIES OF MPW DISCHARGE AT RIVER MOUTH OF THE THA CHIN RIVER (RED LINE) FOR THE MID-POINT SCENARIO AND THE RIVER DISCHARGE (BLUE LINE, REVERSE RIGHT AXIS)
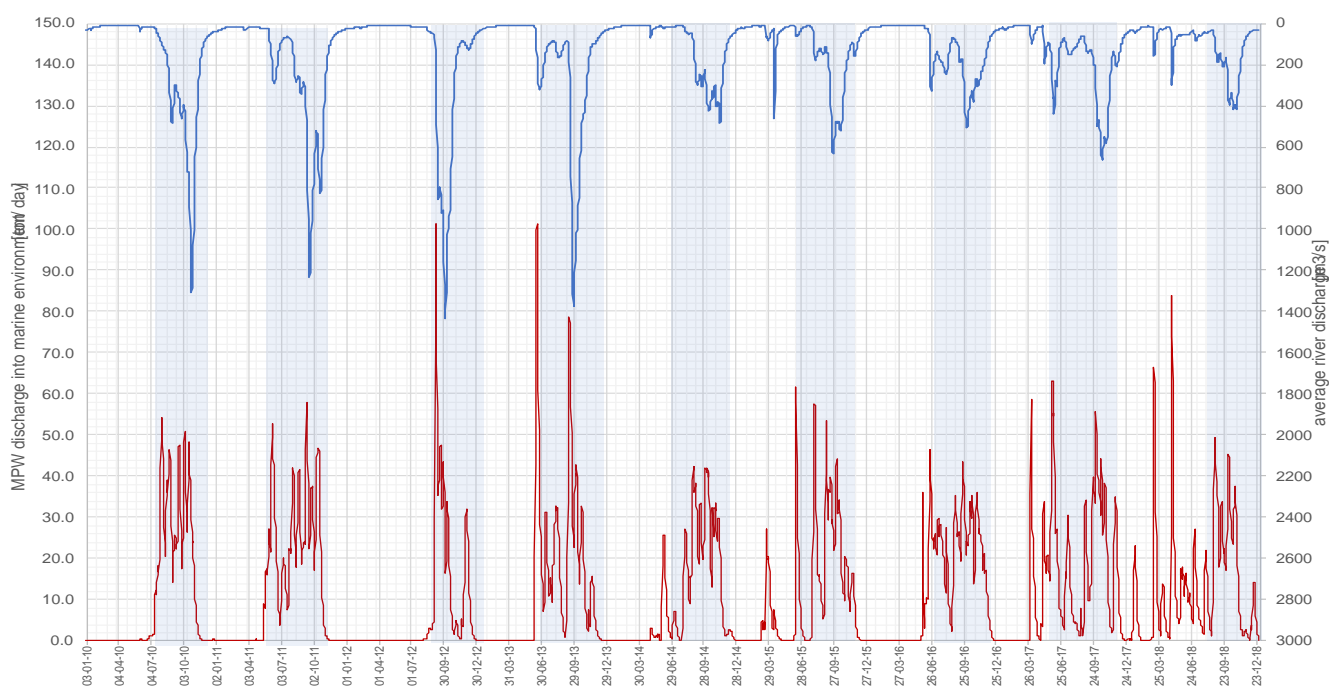
Source: Original calculations for this publication.

Figure 23.
MODELED TIME SERIES OF MPW DISCHARGE AT RIVER MOUTH OF THE CHAO PHRAYA RIVER (RED LINE) FOR THE MID-POINT SCENARIO AND THE RIVER DISCHARGE (BLUE LINE, REVERSE RIGHT AXIS)
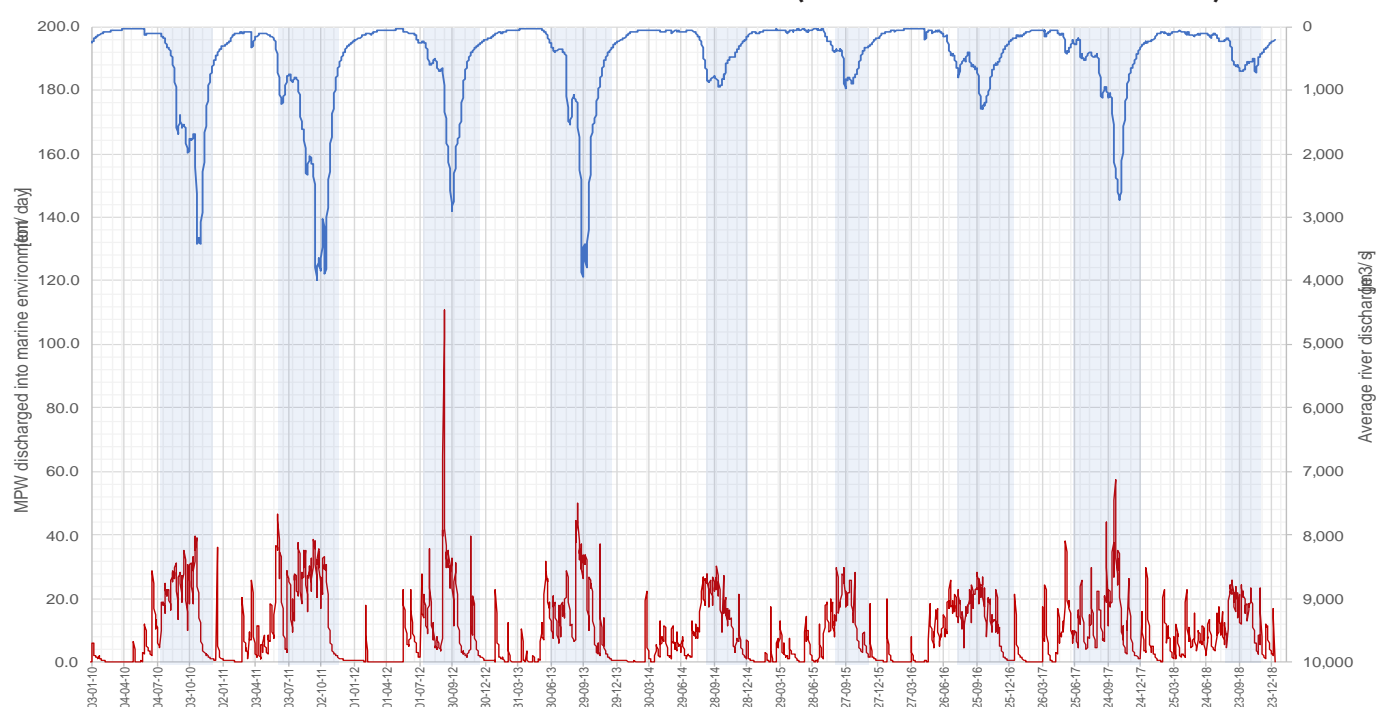
Source: Original calculations for this publication.

although longer-term observations are rare and more long-term continuous field observations are needed in Thailand to further confirm these trends.

Plastic Discharges from Rivers to the Marine Environment in the Top 10 Critical Districts

The fate of the exposed MPW that leaks into the terrestrial and riverine environment in the top 10 critical districts (Table 11) shows that the amount of MPW that remains in the terrestrial and riverine environments varies significantly between different districts. In Bangkok (and elsewhere), multiple dams and weirs are constructed that are assumed to capture all MPW that enters a waterway upstream of these structures. This is reflected by the high percentage of MPW that remains in the riverine system in the districts Klong Sam Wa, Nong Chok, and Phasi Charoen and even in Mueang Chon Buri.

The relative importance of the critical districts changes significantly when hydrology is considered. For instance, it becomes clear that although the collection rate in Mueang Chon Buri is very low, it is likely that investing to improve collection rates in the much bigger district of Mueang Nonthaburi has a much greater effect

in reducing the discharge of MPW into the marine environment. Mueang Nonthaburi becomes the district that contributes most to discharged MPW.

The top 10 critical districts relative to importance regarding discharge of MPW into the marine environment (Table 12), account for about 59.7 percent of exposed MPW discharged into the marine environment. However, these districts account for just 45.1 percent of the total amount of exposed MPW generated in the high-priority catchments.

In a spatial representation (Figure 24), it is also clear that districts closer to the sea and/or closer to the bigger rivers have a higher relative contribution to the amount of MPW discharged into the marine environment. This is in line with expectations.

Figure 24 also shows that the districts close to the main barrage in the Chao Phraya—which forms the border between the lower and upper Chao Phraya catchments—become more important when addressing marine debris. Therefore, it is crucial to validate the assumptions made in this assessment (e.g., that all waste is trapped behind the main barrage).

Table 11.
TOP 10 DISTRICTS BASED ON EXPOSED MPW FROM LAND-BASED SOURCES

ID	District	Exposed MPW (kton/year)				Relative Contribution	Final Destination of Exposed MPW			Relative Contribution to Total MPW Discharge
		Point	Diffuse				Terrestrial	Riverine	Marine	
		Dry	Dry	Wet	Total					
TH2006	Phanat Nikhom	0.32	4.63	-	4.95	9.4%	3.53	0.69	0.73	7.4%
TH2002	Ban Bueng	3.14	0.27	-	3.41	6.4%	2.88	0.33	0.21	2.1%
TH7401	Mueang Samut Sakhon	3.23	-	-	3.23	6.1%	2.24	0.30	0.69	7.0%
TH1046	Khlong Sam Wa	-	2.49	0.10	2.59	4.9%	1.58	0.63	0.39	4.2%
TH1201	Mueang Nonthaburi	-	0.83	1.65	2.48	4.7%	1.23	0.58	0.67	11.3%
TH2001	Mueang Chon Buri	0.24	2.01	-	2.25	4.3%	1.76	0.11	0.39	4.0%
TH1003	Nong Chok	-	2.14	0.09	2.23	4.2%	1.35	0.57	0.31	3.3%
TH7301	Mueang Nakhon Pathom	0.55	1.66	-	2.21	4.2%	1.29	0.34	0.57	5.9%
TH2401	Mueang Chachoengsao	2.14	-	-	2.14	4.0%	1.22	0.54	0.38	3.9%
TH1022	Phasi Charoen	-	2.04	0.08	2.12	4.0%	0.93	0.69	0.51	5.3%

Table 12.
TOP 10 DISTRICTS BASED ON DISCHARGE OF MPW INTO THE MARINE ENVIRONMENT

| ID | District | Exposed MPW (kton/year) | | | | Relative Contribution | Final Destination of Exposed MPW | | | Relative Contribution to Total MPW Discharge | Urban | Rural | Primary Sources of Exposed MPW | | | |
		Dry	Dry	Wet	Total		Terrestrial	Riverine	Marine				SWG/Cap	Collection Rate	Open Dump (kton/year)	Direct to Water (kton.year)
TH1201	Mueang Nonthaburi	-	0.83	1.65	2.48	4.7%	0.41	0.96	1.11	11.3%	79.7%	20.3%	1.24	75.1%	-	1.65
TH2006	Phanat Nikhom	0.32	4.63	-	4.95	9.4%	3.53	0.69	0.73	7.4%	3.2%	96.8%	0.91	34.8%	3.17	-
TH7401	Mueang Samut Sakhon	3.23	-	-	3.23	6.1%	2.24	0.30	0.69	7.0%	5.3%	94.7%	0.85	94.2%	30.94	-
TH7301	Mueang Nakhon Pathom	0.55	1.66	-	2.21	4.2%	1.29	0.34	0.57	5.9%	32.6%	67.4%	1.17	89.6%	1.56	-
TH1206	Pak Kret	-	0.41	0.83	1.24	2.3%	0.22	0.47	0.56	5.7%	64.1%	35.9%	1.49	77.0%	-	0.83
TH1022	Phasi Charoen	-	2.04	0.08	2.12	4.0%	0.89	0.71	0.52	5.3%	100.0%	0.0%	1.58	68.7%	-	0.08
TH1019	Taling Chan	-	1.73	0.07	1.80	3.4%	0.89	0.45	0.46	4.7%	100.0%	0.0%	1.58	70.4%	-	0.07
TH1046	Khlong Sam Wa	-	2.49	0.10	2.59	4.9%	1.52	0.66	0.41	4.2%	100.0%	0.0%	1.58	68.7%	-	0.10
TH1016	Bangkok Yai	-	0.96	0.04	1.00	1.9%	0.32	0.28	0.40	4.1%	100.0%	0.0%	1.58	69.2%	-	0.04
TH2001	Mueang Chon Buri	0.24	2.01	-	2.25	4.3%	1.76	0.11	0.39	4.0%	15.4%	84.6%	0.79	51.5%	2.42	-

Figure 24.
RELATIVE CHANGES IN PRIORITY RANKING FOR DISTRICTS WHEN HYDROLOGY IS CONSIDERED
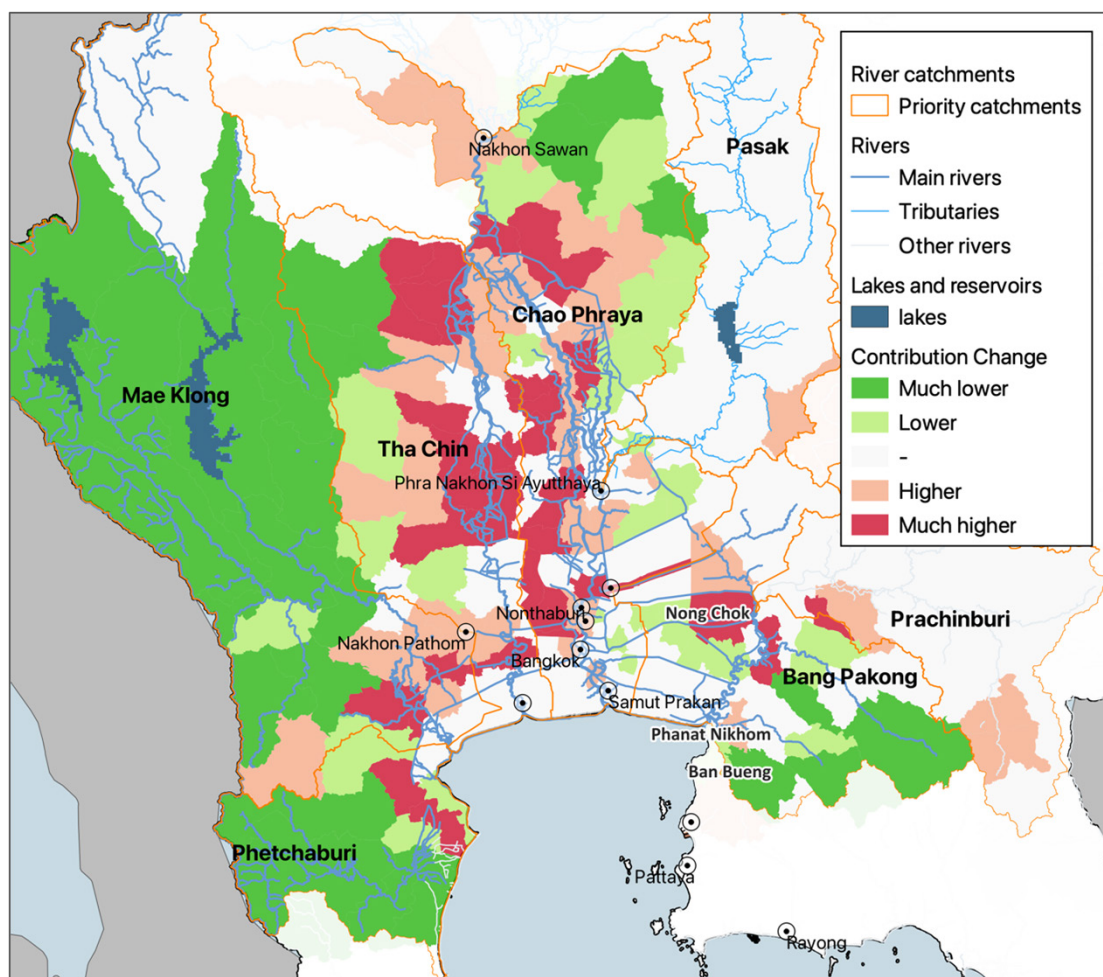
Source: Original calculations for this publication.

3.2.2 Estimation of MPW Discharges from Tourist Hotspots

The fate and transport model indicates that from the tourist hotspots, about 88.6 percent of exposed MPW available for wash-off (i.e., resulting from illegal dumping/fly-tipping and exposed MPW leaked from controlled dumps and open dumpsites) remains in the terrestrial environment (e.g., buried by natural processes). Only 10.2 percent of exposed MPW washes off directly or is transported via waterways into the marine environment. In the waterways, only 1.3 percent of the total exposed MPW gets buried or stored. This is much less compared to the large catchments and is mostly a direct result from the limited length of the waterways on the islands. The model results for the islands are considered uncertain as the models could not be validated directly due to unavailable observation data.

Time series of plastic discharges into the marine environment were generated for the different outlet points (rivers and coasts) of the tourist hotspots. As with the high-priority catchments, analyzing these results shows that climatic variabilities are high and indicate that during wet years, expected annual MPW discharges are much higher compared to dry years.

The spatial representation of Phuket and Krabi (Figure 25) also indicates that in Phuket most MPW enters the marine environment around Phuket town (the calculation is based on the NSO's survey percentage).

3.3. CONFIDENCE AND VALIDATION OF RESULTS

Modeling results have been validated against a number of available datasets to indicate the ability of the various models to represent the actual conditions. In general, only limited data are available to accurately validate

Figure 25.

SPATIAL DISTRIBUTION OF EXPOSED MPW (GREY SHADES) AND THE RESULTING MID-POINT ESTIMATES OF MPW DISCHARGED INTO THE MARINE ENVIRONMENT (BLUE CIRCLES) FROM RIVER MOUTHS AND COASTAL AREAS
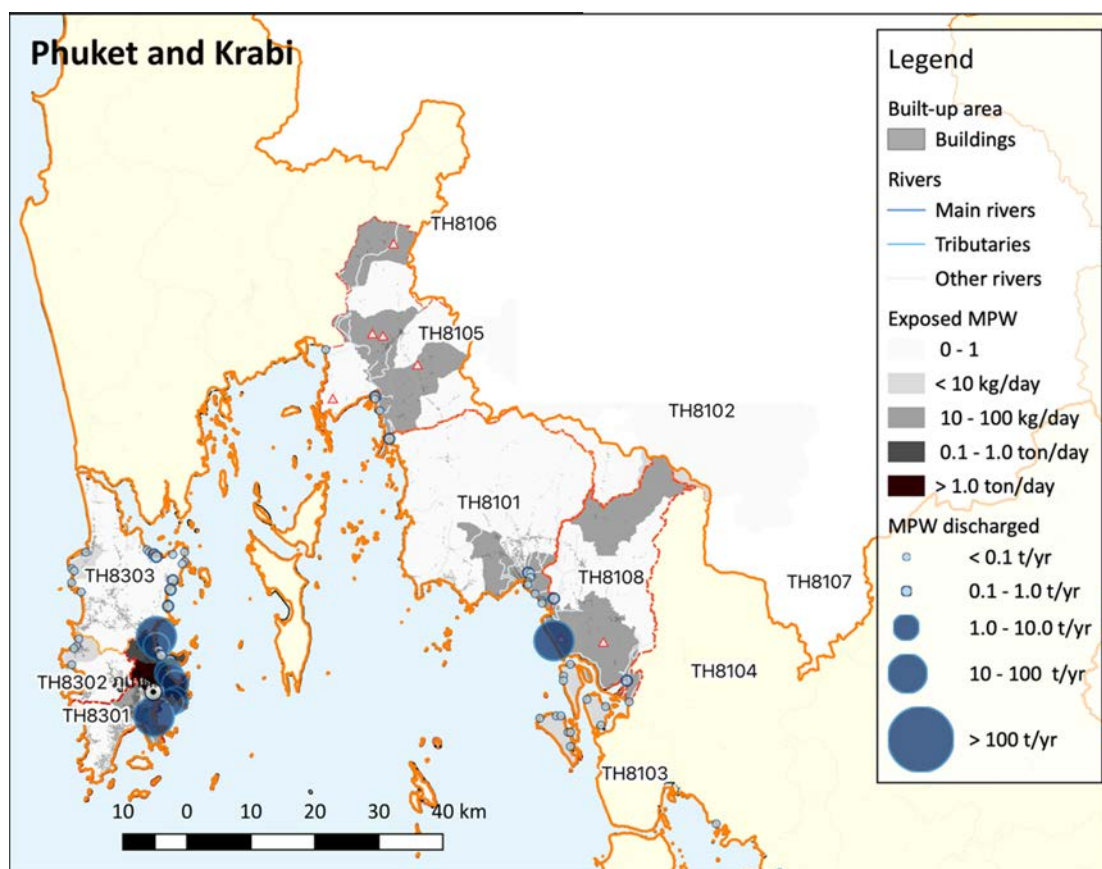
Source: Original calculations for this publication.

the models. Further details on the validation for the different components are provided in Appendix E.

3.3.1 SWM Model

Confidence of Input Data and Results

There is some uncertainty associated with the input data for the SWM model. Three scenarios (low, mid and high estimates) were produced for SWG per capita and plastic content as a result. In Thailand, no detailed data is available on SWG per capita at (sub)district or LAO level. SWG per capita rates were estimated based on the available downstream data (reported formally collected waste from PCD and LAOs and reported collection rates from NSO with low, mid and high estimates developed in line with the (inter) national literature). The three scenarios of input data were then used to establish estimates for exposed MPW which are used to simulate actual wash-off and transport of MPW from land-based sources to the marine environment as described in section 2.3. This

significantly increases the uncertainty of the results, especially at the lowest levels (subdistrict and LAO level). At catchment level, this translates into a very wide range (difference between the low and high scenarios) for MPW discharged into the marine environment. The available data did not allow for a detailed statistical analysis (such as a Monte Carlo analysis[13]) over the entire waste flow model, which should be considered when more detailed SWM data are available.

Hydrological variability due to daily, seasonal and annual rainfall was also accounted for. The datasets used to construct the SWM database are mostly based on data obtained for 2018 and the SWM model results are therefore considered to represent the 2018 situation. The hydrological effects on MPW wash-off and transport were estimated using a historical (spatially representative) rainfall dataset for the period January 2010 to December 2018, with daily rainfall

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13 Computational simulation of repeated sampling to generate a range of possible values.

estimates at a high spatial (1 km²) and temporal (daily) resolution. The results account for the wide variability of precipitation in Thailand and the results reflect the daily variability and seasonality of MPW loads in the riverine environment in the high-priority catchments. The simulations result in time series for MPW discharged into the marine environment. For each of the three scenarios the minimum, average and maximum annual (for a moving 365-day period) discharges of MPW into the marine environment were determined. These estimates are considered representative for dry, average and wet years.

As such the results provide insight in both uncertainty of SWM data and the range due to climatological variations. The study results indicate that the climatological variations result in expected discharges during a wet year to be about twice the discharges expected during a dry year. The uncertainty in SWM data is much wider and the difference between the low-end estimate and high-end estimate is roughly a factor of 4.5.

Validation of Input Data and Results

Overall, based on the available local SWM data, it was possible to generate a realistic spatial distribution of managed and mismanaged (plastic) waste. However, because there is uncertainty with regard to the amount of (plastic) waste that is exposed and therefore available for wash-off at the various unsanitary disposal facilities, the results for the catchments with a significant number of unsanitary disposal facilities are considered to be less certain. See Figure 26 for a depiction of confidence levels for the various study areas.

3.3.2 Hydrological Models

The model results for the Phetchaburi and Mae Klong catchments are slightly uncertain (reasonably confident to confident) because in these catchments, irrigation schemes are present. These irrigation schemes extract water from the river. No data was available to account for these abstractions in the model.

The number of irrigation schemes in the Phetchaburi is limited and therefore the results of this catchment are still considered sufficient for the purposes of this study. The model results of other catchments are considered good to very good.

No validation datasets were available for the tourist hotspots and therefore the hydrological models for these domains could not be calibrated. The results for these areas are considered highly uncertain and require further validation/calibration. See Figure 27 for a depiction of confidence levels for the various study areas.

3.3.3 Fate and Transport Models

Based on the validation of the model results with observation datasets from the BMA and the Department of Marine and Coastal Resources (DMCR) (see Appendix E), it is concluded that the models for the Tha Chin, Chao Phraya and Bang Pakong Rivers perform very well and the model for the Phetchaburi River performs well during the wet season, but less otherwise.

Of the well-performing models, the model results from the mid-point (Tha Chin) and high-end (Phetchaburi, Chao Phraya and Bang Pakong) scenarios are in line with the field observations (data obtained from DMCR), and are in line with the estimated monthly average plastic loads retrieved from riverine debris

Figure 26.
CONFIDENCE LEVELS FOR THE VARIOUS STUDY AREAS, BASED ON THE VALIDATION OF THE SWM MODEL

Model	Confidence Level	Phetchaburi	Mae Klong	Tha Chin	Chao Phraya	Bang Pakong	Krabi	Phuket	Ko Samui
	Confident		●	●				●	
SWM	Reasonably Confident	○			○	○	○		○
	Uncertain								

Note: Details on the validation for each of the data inputs to the SWM model are provided in Appendix E.

Figure 27.
CONFIDENCE LEVELS FOR THE VARIOUS STUDY AREAS, BASED ON THE VALIDATION OF THE HYDROLOGICAL MODEL

Model	Confidence Level	Phetchaburi	Mae Klong	Tha Chin	Chao Phraya	Bang Pakong	Krabi	Phuket	Ko Samui
HYDROLOGY	Confident	■		■	■	■			
	Reasonably Confident	■	■						
	Uncertain						■	■	■

Note: Details on the hydrological model validation are provided in Appendix E.

(data obtained from the BMA). We conclude that the model results of the Tha Chin are very good and the results of the Phetchaburi, Chao Phraya and Bang Pakong catchments are somewhat uncertain. See Figure 28 for a depiction of confidence levels for the various study areas.

The model results of the Mae Klong and the small islands are considered uncertain:

- The model for the Mae Klong does not perform well throughout the year. This is likely because the wflow_sbm model is not representative for low runoff and low discharge conditions and is further reduced because of the uncertainty of the operational conditions of the irrigation schemes and the dam in the downstream reach of the river.

- The models for the small islands could not be validated directly because no observation data is available. To get an indication of performance, the model results are compared to the results obtained with the models of the main catchments. The models for the small islands likely underperform (caused by the underperforming hydrological models) and the estimated MPW discharges are likely underestimated.

3.4 COMPARISON WITH PREVIOUS COMPLEMENTARY ESTIMATES

It is difficult to compare the modeled estimates for MPW in the high-priority catchments with (inter) national studies because the (inter)national studies have a different geographical (mostly national) focus. Benchmarking to these studies is required to be able to put the results of this study in perspective. When we consider that the high-priority catchments with confident results covering approximately 34.1 percent of the population, the results of the (inter)national studies can be downscaled relative to the covered population. By doing this, no justice is done to the

Figure 28.
CONFIDENCE LEVELS FOR THE VARIOUS STUDY AREAS, BASED ON THE VALIDATION OF THE FATE AND TRANSPORT MODEL

Model	Confidence Level	Phetchaburi	Mae Klong	Tha Chin	Chao Phraya	Bang Pakong	Krabi	Phuket	Ko Samui
FATE AND TRANSPORT	Confident			■					
	Reasonably Confident	■			■	■			
	Uncertain		■				■	■	■

Note: Details on the fate and transport model validation are provided in Appendix E.

actual conditions nor the intentions of the individual studies. However, since the intention of this exercise is only to compare results of this study with results from available peer-reviewed international studies, this method provides an opportunity to do so.

The confident results are presented in Table 13 alongside results from existing (inter)national studies. The results of this study are on the lower end of previous studies. The existing studies have their own caveats, which are further discussed in this section.

In general, most previous global studies (for example, Jambeck et al. 2015) tend to be biased toward European and North American rivers and the available studies on riverine plastic debris focus mainly on plastic in rivers with large basins, although such basins are not necessarily the largest contributors to the ocean plastic pollution. In addition, plastic transport and composition are often not measured consistently over time and geographic areas, with numbers averaged instead.

So far, existing (inter)national studies have not included hydrology as a driver for wash-off and transport, and do not use local SWM data and handling practices, relying on national averages instead.

Downscaling the results of available (inter)national studies to the covered population in this study allows for comparison with previous peer reviewed (inter) national studies. This shows that the estimated SWG and PWG figures are in the same order as reported and presented in the (inter)national literature. This indicates that the results of the SWM model are realistic and gives confidence to MPW and discharge results (for the catchments with confident results).

This study puts a mid-point estimate for MPW at 388.6 kton/year (range 178.7–1,002.2 kton/year). The mid-point estimate is slightly higher than the downscaled Jambeck et al. (2015) figure. It must be noted that Jambeck et al. (2015) based their assessment only on plastic waste generated by the population living within 50 km of the

Table 13.
COMPARING MODELED RESULTS WITH (INTER)NATIONAL LITERATURE

Research/ Study	Year	Population (People)	Coverage (%)	SWG (kton/ year)	Plastic Content (%)	PWG (kton/ year)	MPW (kton/ year)	MPW per Capita (kton/ year)	Exposed MPW (kton/ year)	Exposed MPW per Capita (kg/yr/ cap)	Discharged MPW (kton/year)
This study confident results[14]	(mid)	23,146,449	34.1%	10358.3	17.4%	1799.7	385.9	16.79	49.9	2.13	9.3
	range			8,503.5 - 13,715.8		1,221.0 - 2,878.2	178.5 - 998.1	7.72 - 43.30	8.9 - 189.1	0.38 - 8.17	1.9 - 32.3
PCD	2018	67,936,438	100.0%	27,800.0	17.0%	4,730.0[15]	N/A	N/A	N/A	N/A	N/A
	downscaled	23,146,449[16]	34.1%	9,471.7		1,611.5					
Bureecan et al	2017	N/A[3]	100.0%	N/A	N/A	3,560.0	1,070.0	N/A	N/A	N/A	N/A
	downscaled		34.1%			1,212.9	364.6				
Chula-longkorn	2017	N/A[3]	100.0%[17]	15,800.0[18]	20.0%	1,930.0	30.0	N/A	10 - 30		10 - 30
	downscaled		34.1%	5,383.2		657.6	10.2		3.4 - 10.2		3.4 - 10.2
Jambeck et al	2015	26,000,000[19]	41.9%[20]	31,200.0	12%	3,740.0	1,030.0	39.62%	N/A		150 - 470
	downscaled	3,714,810[3]	14.3%	4,457.8		534.4	147.2				51.1 - 160.3

14   Covers the Bang Taboon, Tha Chin, Chao Phraya and Bang Pakong catchments only

15   Not in the PCD report, estimates prepared by Deltares et al using 17.0% plastic content

16   Reported figures downscaled to the coverage of the 4 catchments with confident model results

17   Only based on 11 target products

18   Only accounted for formal collection

19   Only coastal population, within 50km from coast

20   Total population in Thailand in 2010 was approximately 62 million

coast (using the population of 2010) while this study calculated MPW generated by the entire population in the high-priority catchments only (representative for 2018 and including the BMA).

Total exposed MPW in the catchments with confident results is estimated at 51.5 kton/year (range 8.9–189.1 kton/year). This is considerably higher than the results from Chulalongkorn University (2017), which puts a national figure at 10–30 kton/year. The models indicate that a large amount of exposed MPW remains in the terrestrial and riverine environments, and for the four catchments with reliable results, discharged MPW is estimated at 9.3 kton/year (range 1.9–32.3 kton/year). The range is in the same order but wider than the estimated range by Chulalongkorn University

(2017) (downscaled 3.4–10.2 kton/year). However, the estimated range is considerably lower than Jambeck et al. (2015). This is because this study:

- Uses actual local SWM data (2018).

- Accounts for different handling practices of uncollected waste (open burning, fly-tipping, disposal in water and others).

- Uses actual locations for point sources (controlled dumps and open dumpsites).

- Only considers a part of MPW available for wash-off (exposed MPW).

Jambeck et al. (2015) do not consider these and build on national reported SWM data from 2010.

Photo: Shutterstock / Wachiwit.

SECTION 4.
CONCLUSIONS AND RECOMMENDATIONS

This study has built material flow models for the five high-priority catchments around Bangkok that discharge into the Upper Gulf of Thailand and for three tourist hotspots (Phuket, Krabi and Ko Samui). These models provide insight into plastic waste generation and handling practices in these areas and show how these translate into plastic waste leakages and discharges into the marine environment. The high spatial resolution resulting from the SWM model built on local data has provided important insights that can direct policies, measures and investments, and can inform the National Marine Debris Action Plan to reduce marine debris in the most effective way. The results show that a more ambitious target to reduce marine debris could even be possible when measures are focused on the most critical districts.

By integrating the best available local data and incorporating realistic hydrological processes and state-of-the-art transport modeling, this approach makes considerable progress in assessing plastic pollution from land-based sources in Thailand. Similar to its application elsewhere in the region (World Bank 2021), the value of this methodology to inform policy includes:

- Establishing realistic baselines of plastic waste discharges for four of the catchments against which progress can be measured.

- Helping to set differentiated priorities between catchments and districts by providing local insight into the (relative) contribution of those districts and specific waste handling practices to the plastic waste pollution.

- Exploring different scenarios of investment and policy interventions through assessing potential impact of measures on the reduction of plastic discharges.

- Helping to determine optimal observation sampling intervals to reliably draw conclusions on the effectiveness of implemented policy measures and investments.

There are, nevertheless, scope and opportunities for further improvement. The production of better solid waste dataflows and accurate hydrological models, long time series of field observations, as well as new emerging knowledge on plastic waste leakages (especially from unsanitary disposal facilities) and riverine transport processes will enable this approach to be further refined and validated, while reducing the range of uncertainty.

Comparison with field observations (obtained from DMCR for the period December 2016 to August 2019) shows good correlation of model results with discrete observations. Also, noting the limitations of the scarce field observation data in representativeness for annual trends (if at all), the study's conclusion that MPW discharges from individual rivers during wet years may be double of what they may be during a dry year seems to be confirmed by the field observations. It is therefore cautiously concluded that the trend (that MPW discharges are reducing) that may be observed in the observation data from DMCR is, at least partly, a result of climatic variations. Ongoing observation data may be able to confirm this.

While the SWM model performs well for all assessed areas, it was concluded that the hydrological and fate and transport models for the tourist hotspots and the Mae Klong catchment underperform. Therefore, results of the fate and transport model of the tourist hotspots and the Mae Klong catchment are not presented in this chapter.

This chapter presents the key conclusions of the assessment that can help inform decision-making and provides recommendations on how this approach can be improved for future assessments and use in the Thai context. The key conclusions are presented as answers to the first two research questions:

1. How much plastic waste is being discharged into the marine environment?

2. Where does this plastic waste come from?

The recommendations provide the answers to the last question:

3. What can Thailand do to reduce the discharge of plastic waste into the marine environment?

The final part of this chapter concludes with recommendations to improve the data and models that are essential for monitoring and evaluating the effectiveness of policy options and progress.

4.1 KEY RESULTS AND CONCLUSIONS OF THE ASSESSMENT

Figure 29 presents the Sankey diagram for the four high-priority catchments with reliable results (Phetchaburi, Tha Chin, Chao Phraya and Bang Pakong) — from top to bottom showing the flow of plastic from generation, collection, disposal and then pathways through the environment.

4.1.1 How much plastic waste is being discharged into the marine environment?

The mid to high-end scenarios from the SWM model are considered the scenarios that resemble the actual SWM situation closest. The mid scenario shows that the volume of MPW generated in the study areas is estimated to total about 444.8 kton/year (428.0 kton/year in the high-priority catchments and 16.8 kton/year in the tourist hotspots). It is estimated that only 2.8 percent of plastic waste generated and 12.4 percent of MPW generated may be available for wash-off and is considered exposed MPW (49.9 kton/year in the four catchments).

When hydrology is considered, it was found that across the four catchments about 81.0 percent of exposed MPW remains in the environment and only 19.0 percent (9.3 kton/year) is discharged into the marine environment. This represents only about 0.55 percent of the total amount of plastic waste that is generated in these areas. Across the four catchments an average 37.0 percent of exposed MPW in the terrestrial environment is estimated to wash off to a waterway and 63.0 percent remains in the dry terrestrial environment. Of the exposed MPW that enters the riverine environment (through actual wash-off or from direct disposal in waterways), an average of 47 percent is being discharged into the marine environment and 53 percent remains trapped in the riverine environment.

The study results indicate that, following the mid scenario, from the four high-priority catchments with reliable results, an annual average total of 9.3 kton/year of plastic waste is discharged into the marine environment. This is equivalent to a marine plastic footprint of 0.4 kg/capita/year. During particularly rainy years this may increase to 14.3 kton/year and during drier years it may be as low as 4.9 kton/year. Although the total amount of MPW generated is a significant amount, most (exposed) MPW remains in the terrestrial and riverine environments.

It was shown that most plastic waste is discharged during the rainy season: over the simulated period, in the four catchments combined an average of 79.6 percent of the total MPW discharged into the marine environment was modeled as discharged during the rainy season. It was also shown that exposed MPW that has accumulated on land during an extended drier period can wash off during a rainfall event in the dry season, resulting in a brief but high load of plastic waste discharged into the marine environment.

4.1.2 Where does the discharged plastic waste come from?

It was found that formal collection (60.3 percent) and recycling (28.5 percent) rates across the studied areas are high with a combined rate of 88.8 percent. However, across the studied areas a significant amount of waste remains uncollected and there is a large number of formal unsanitary disposal facilities where (plastic) waste may leak into the environment. In Thailand, the population has a general preference to burn uncollected waste (80.7 percent of uncollected waste

Figure 29.

SANKEY DIAGRAM FOR THE FOUR HIGH-PRIORITY CATCHMENTS SHOWING AN APPROXIMATION OF THE PLASTIC WASTE MATERIAL FLOW FROM GENERATION TO DISCHARGE TO THE MARINE ENVIRONMENT

Plastic Waste Generation

100%

Formally Collected 89.0%

Uncollected 11.0%

Disposed to Unsanitary Facilities 15.0%

Other 0.6%

Openly Burned 8.7%

Disposed on Land 1.5%

Disposed to Sanitary Facilities 52.6%

Recycled 21.4%

Disposed in Rivers 0.2%

Not Exposed to Environment 13.9%

Exposed to Environment 1.1%

Dry Environment

Washed-off to Rivers 0.9%

Washed-off to and Directly Disposed in Rivers 1.1%

Retained in Soils 1.7%

Discharged into Marine Environment 0.5%

Retained in Rivers/ Captured by Dams 0.6%

- - - - - Possible pathways for plastic waste material flow from generation to the marine environment

Source: Original figure for this publication.

Figure 30.

ORIGIN OF EXPOSED MPW (LABELS IN KTON/YEAR) IN FOUR CATCHMENTS WITH CONFIDENT RESULTS ONLY (BASED ON NSO'S SURVEY PERCENTAGE)
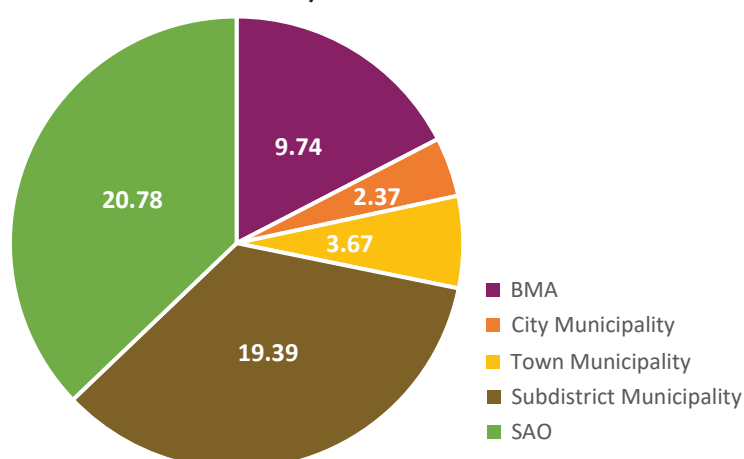
Source: Original calculations for this publication.

is burned) although this is less common in the urban areas. Burned (plastic) waste is assumed to not wash-off and is therefore not considered exposed MPW.

Across all studied catchments and districts, 58.1 percent of exposed MPW comes from uncollected waste (32 kton/year) and 41.9 percent comes from unsanitary disposal facilities (23.1 kton/year) (mainly open dumping).

Most exposed MPW is generated in the rural districts (37.4 kton/year or 70.1 percent) (smaller subdistrict municipalities and SAOs) where collection rates are generally much lower than in cities and where in general most disposal facilities (including in some cases for urban areas) and open dumping locations can be found. In addition, also in the Bangkok Metropolitan region a significant amount of exposed MPW is generated. Although the collection rate in Bangkok is high, the large volumes of waste generated result in a still significant overall volume of exposed MPW of 9.7 kton/year (18.4 percent of total exposed MPW generated). See Figure 30 for a breakdown by origin.

In general, it was found that with increasing distance to the sea, the relative amount of plastic waste that enters the marine environment becomes smaller, due to retention and removal processes. This underscores that priority should be given to addressing solid waste problems in districts closer to the sea and downstream of the dams.

Looking at the individual catchments, it was found that 9.3 kton/year enters the marine environment from the Phetchaburi (0.04 kton/year, 0.5 percent), Tha Chin (4.0 kton/year, 43.2 percent), Chao Phraya (3.5 kton/year,

37.1 percent), and Bang Pakong (1.8 kton/year, 19.3 percent) rivers.

Although there is considerable uncertainty with regard to the results for the tourist hotspots and the Mae Klong River catchment, it is not expected that these areas combined will contribute significantly to marine debris. These areas combined generate only 9.2 percent of total exposed MPW while the four other catchments combined generate 90.8 percent.

4.2 RECOMMENDATIONS FOR POLICY AND INVESTMENTS

The following recommendations have been formulated based on the results of the assessment and can be considered in view of reducing the flow of plastic waste from land-based sources into the marine environment. Concrete recommendations for short- and medium-term actions for the districts that most contribute to exposed MPW and MPW discharged into the marine environment are provided.

Recommendations to reduce discharge of plastic waste to marine environment are identified at different locations in the waste flow diagram. While it is generally agreed that measures to reduce plastic waste generation are most effective and sustainable in the long term, there are multiple useful measures that can prevent plastic leakages and may be effective and/ or cost-effective in the short term. From the waste flow diagrams it becomes clear that measures downstream in the waste chain are expected to be more efficient in reducing marine debris. For example, reducing direct disposal to water by 1 kton/year is expected

to result in an average reduction of 0.4 kton/year in plastic discharge, while to obtain the same reduction in discharged plastic waste through reducing plastic waste generation in total, plastic waste generation needs to be reduced by almost 175 kton/year. However, measures upstream in the waste chain have many other benefits and may still be preferable.

In this section, based on the study results, concrete measures and policy recommendations are provided to:

1. Reduce transport of leaked MPW (downstream in waste chain).

2. Reduce MPW generation (mid-stream in waste chain).

4.2.1 Measures to Reduce Transport of Leaked MPW (Downstream in Waste Chain)

Measures to capture MPW leaked or about to leak into waterways can be most effective in reducing marine debris in the short term. For example, these can be particularly advantageous if they make use of existing infrastructure and therefore can be implemented at short notice. It is recommended to optimize the use of existing structures in waterways and drainage systems to prevent plastic waste from reaching the marine environment.

Initially, focus on areas at close distance from the coast (but also consider installing them elsewhere), including those districts listed in Table 14.

- In urban areas: Install trash racks in urban drainage systems, just before the outlet to a main river or waterway and clean them daily.

- In rural areas: Install trash racks in irrigation canals just downstream from villages.

- In rivers: Promote and expand river clean-up initiatives such as the one managed by the BMA in the Chao Phraya River.

It is recommended, as a first next step, to analyze possible existing constraints to the required investments to install such equipment. It is noted that these measures do not require large financial investments and there may be existing constraints that prevent this from happening, such as operational costs.

In addition, intercepting waste as it is carried downstream provides an excellent opportunity to monitor plastic waste in the riverine environment.

Table 14.
TOP 10 CRITICAL DISTRICTS ACCORDING TO EXPOSED MPW WASHED OFF FROM DIFFUSE SOURCES

ID	District	Exposed MPW (kton/year)			Relative Contribution	Population			Primary Source of Exposed MPW		
		High	Med	Low		Total	Urban	Rural	Collection Rate	Direct to Water (kton/year)	Fly-tipping (kton/year)
TH2006	Phanat Nikhom	7.11	5.18	0.12	11.6%	203,656	3.2%	96.8%	34.8%	-	4.87
TH1201	Mueang Nonthaburi	6.28	2.48	0.24	10.4%	656,021	79.7%	20.3%	75.0%	1.65	0.83
TH1022	Phasi Charoen	4.20	2.12	-	9.9%	215,153	100.0%	0.0%	68.7%	0.08	2.04
TH1046	Khlong Sam Wa	3.01	1.52	-	8.4%	263,088	100.0%	0.0%	68.7%	0.06	1.46
TH1003	Nong Chok	4.17	2.23	-	7.3%	195,069	100.0%	0.0%	63.8%	0.09	2.14
TH1019	Taling Chan	3.63	1.80	-	7.2%	192,590	100.0%	0.0%	70.4%	0.07	1.73
TH1206	Pak Kret	2.14	1.53	0.06	6.0%	363,905	64.1%	35.9%	76.9%	1.02	0.51
TH1016	Bangkok Yai	2.00	1.00	-	5.5%	103,306	100.0%	0.0%	69.2%	0.04	0.96
TH7305	Bang Len	2.52	1.39	0.76	4.3%	106,318	0.0%	100.0%	59.4%	-	1.38
TH2001	Mueang Chon Buri	4.56	2.25	0.09	3.7%	129,214	15.4%	84.6%	51.5%	-	2.01

This data is currently largely lacking and it is urgently required to validate and improve the other datasets and models and evaluate the effects of policy interventions.

4.2.2 Measures to Reduce MPW (Mid-stream in Waste Chain)

Measures to reduce MPW focus on improving solid waste management practices, services to collect more solid waste and improve final disposal to prevent leakages into the environment. Following the identified main sources of MPW (unsanitary disposal facilities and uncollected waste), the following measures are identified (the high-priority districts based on their relative contribution to marine debris are indicated with an *):

1. Further improve waste collection in urban areas

Collection rates in the urban areas are fairly high (in Bangkok about 85 percent of waste is formally collected). However, considering the large urban population, a significant volume of waste remains uncollected in the urban areas. Some of this waste finds its way to waterways and the marine environment.

Investments to improve collection rates in the urban areas should start with the districts that contribute most to the exposed MPW from uncollected waste in the Chao Phraya and Bang Pakong Rver catchments (Table 15).

2. Develop an efficient waste collection system in rural Thailand

Uncollected plastic waste accounts for about 50–70 percent of marine debris. It is mostly in rural areas where a significant part of solid waste remains uncollected (across the study area approximately 21 percent). In these areas most uncollected waste is burned by people (almost 90 percent) and only a fraction is expected to reach the marine environment. Because of the diffuse nature of this problem, it is recommended to invest in the development of an efficient waste collection system for rural Thailand. In Thailand, SWM is the responsibility of the LAOs. Contrary to the larger LAOs (mostly in affluent urban areas), the small LAOs and especially the SAOs in the rural areas have budget constraints and limited expertise to organize proper waste collection and management.

Table 15.
TOP 10 CRITICAL DISTRICTS ACCORDING TO EXPOSED MPW GENERATED IN URBAN SUBDISTRICTS

| ID | Priority | District | Catchment | Exposed MPW (kton/year) | | | | Relative Contribution | Relative Contribution to Total MPW Discharge | Collection Rate | Exposed MPW from Uncollected Waste in Urban Area |
| | | | | Point | Diffuse | | | | | | |
				Dry	Dry	Wet	Total				
TH1046	*	Khlong Sam Wa	Chao Phraya/ Bang Pakong	-	2.49	0.10	2.59	4.7%	1.6%	68.7%	2.59
TH1003		Nong Chok	Chao Phraya	-	2.14	0.09	2.23	4.0%	1.3%	63.8%	2.23
TH1022	*	Phasi Charoen	Chao Phraya	-	2.04	0.08	2.12	3.8%	2.0%	68.7%	2.12
TH1019	*	Taling Chan	Chao Phraya	-	1.73	0.07	1.80	3.3%	1.8%	70.4%	1.80
TH1201	*	Mueang Nonthaburi	Chao Phraya	-	0.83	1.65	2.48	4.5%	4.3%	75.0%	1.72
TH1016	*	Bangkok Yai	Chao Phraya	-	0.96	0.04	1.00	1.8%	1.6%	69.2%	1.00
TH1206	*	Pak Kret	Chao Phraya	-	0.51	1.02	1.53	2.8%	2.7%	76.9%	0.94
TH2011		Ko Chan	Bang Pakong	-	1.33	-	1.33	2.4%	0.3%	39.0%	0.49
TH2001	*	Mueang Chon Buri	Bang Pakong	0.24	2.01	-	2.25	4.1%	1.5%	51.5%	0.49

HEALTH AND ENVIRONMENTAL HAZARDS FROM BURNING (PLASTIC) WASTE

It is generally known that burning plastic is a major source of air pollution. Openly burning plastics releases large amounts of toxic gases that are harmful to humans, vegetation, and animals, and are a source of environmental pollution in general (Verma et al. 2016). The released toxics can cause a wide variety of serious health issues in humans including aggravating respiratory illnesses such as COVID-19 (Zhu et al. 2020).

The top 10 critical districts with regard to exposed MPW from uncollected plastic waste (Table 16), show that addressing this problem is not an easy task. Apart from Phanat Nikhom, the relative contributions of each of the districts is only about 2–4 percent. Therefore, reducing uncollected waste requires a coordinated effort and is likely going to take some time before it really starts to show in reduced MPW discharged into the marine environment.

The central government, through the environmental fund, should promote and support the organization of solid waste management in these LAOs through:

- Evaluation of the collection and transport of solid waste capacity and provide sufficient and suitable machinery, equipment and vehicles.

- Development of a sorting system and collection of waste by classification.

- Training to implement best practices on sorting and collecting, such as separate collection schedules for different types of waste.

- Finding sanitary disposal sites for small LAOs that could join with a close larger LAO based on the cluster.

- In some cases where the disposal site is far away from the collection area, providing a transfer station for waste from remote locations.

Table 16.
TOP 10 CRITICAL DISTRICTS ACCORDING TO EXPOSED MPW GENERATED IN RURAL SUBDISTRICTS

ID	Priority	District	Catchment	Exposed MPW (kton/year)				Relative Contribution	Relative Contribution to Total MPW Discharge	Population		
				Point	Diffuse					Total	Urban	Rural
				Dry	Dry	Wet	Total					
TH2006	*	Phanat Nikhom	Bang Pakong	0.32	4.87	-	5.18	9.4%	3.0%	203,656	3.2%	1.0%
TH2001	*	Mueang Chon Buri	Bang Pakong	0.20	2.01	-	2.25	4.1%	1.5%	129,241	15.4%	84.6%
TH7305		Bang Len	Tha Chin	0.01	1.38	-	1.39	2.5%	1.3%	106,318	0.0%	100.0%
TH7302		Kam Phaeng Saen	Tha Chin	-	1.13	-	1.13	2.0%	0.9%	150,776	0.0%	100.0%
TH7301	*	Mueang Nakhom Pathom	Tha Chin	0.55	1.66	-	2.21	4.0%	2.2%	326,448	32.6%	67.4%
TH7304		Don Tum	Tha Chin	0.10	0.85	-	0.95	1.7%	1.0%	56,942	0.0%	100.0%
TH2011		Ko Chan	Bang Pakong	-	1.33	-	1.33	2.4%	0.3%	59,682	45.4%	54.6%
TH7303		Phutthamonthon	Chao Phraya	-	0.87	-	0.87	1.6%	0.7%	23,866	0.0%	100.0%
TH1201	*	Mueang Nonthaburi	Chao Phraya	-	0.83	1.65	2.48	4.5%	4.3%	656,021	79.7%	20.3%
TH7303		Nakhon Chai Si	Tha Chin	0.21	0.72	-	0.93	1.7%	1.0%	118,971	0.0%	100.0%

3. Invest in well-managed final disposal facilities and upgrade unsanitary disposal facilities (open dumpsites and controlled dumps), giving priority to the facilities nearby waterways

Although Thailand has invested significantly in solid waste management and has constructed many sanitary disposal facilities over the past 10 years, there are still many unsanitary disposal sites (especially in the more rural areas). The PCD already has a list of priority facilities that require attention. This study provides additional information to determine the top priority facilities that are expected to contribute most to marine debris. The top 10 critical districts that accommodate the priority facilities contribute to about 25 percent of total exposed MPW (Table 17).

The top three cover the biggest open dumpsites in the studied area, each with an annual absorption capacity between 100–200 kton/year. These open dumpsites deserve urgent attention and measures should be taken to properly contain waste disposed at these locations.

4. Consider introducing city-wide clean-up sweeps just before the start of the rainy season

The study results indicate that the plastic waste discharge peaks mostly occur during the rainy season.

Therefore, similar to the clean-up activities of the urban drainage systems and the trimming of trees prior to the onset of the rainy season, the LAO should consider increasing the frequency of waste collection prior to and during the rainy season to help reduce the amount of washed-off plastic waste. The government may even consider actively looking for accumulated plastic waste in the area and removing it before it can be washed off, using the weather forecast to plan and coordinate efforts.

5. Improve laws and regulations to support the implementation of measures

Develop a law to enforce MSW separation/sorting at source, separate collection and clustering of local authorities for the management of solid waste, including the regulations on the system for monitoring, control, establishment and operation of waste disposal, and capacity building of the local authority's staff in waste management. The laws to be improved include:

- Act on the maintenance of cleanliness and orderliness of the country 2017
- Announcement of the Ministry of Interior on Waste Management 2017

Table 17.
TOP 10 CRITICAL DISTRICTS ACCORDING TO EXPOSED MPW FROM POINT SOURCES

| ID | Priority | District | Catchment | Exposed MPW (kton/year) | | | | Relative Contribution | Relative Contribution to Total MPW Discharge |
| | | | | Point | Diffuse | | | | |
				Dry	Dry	Wet	Total		
TH7401	*	Mueang Samut Sakhon	Tha Chin	3.23	-	-	3.23	5.8%	2.7%
TH2002		Ban Bueng	Bang Pakong	3.14	0.27	-	3.41	6.2%	0.8%
TH2401		Mueang Chachoengsao	Bang Pakong	2.14	-	-	2.14	3.9%	1.5%
TH1414		Uthai	Chao Phraya	0.87	-	-	0.87	1.6%	0.4%
TH8404		Ko Samui	Ko Samui	0.84	-	-	0.84	1.5%	0.1%
TH1104		Phra Pradaeng	Chao Phraya	0.72	-	-	0.72	1.3%	1.1%
TH7101		Mueang Kanchanaburi	Mae Klong	0.68	0.09	-	0.77	1.4%	0.1%
TH7605		Tha Yang	Bang Taboon	0.65	0.05	-	0.69	1.3%	0.0%
TH1601		Mueang Lop Buri	Chao Phraya	0.63	0.03	-	0.66	1.2%	0.2%
TH7209		U Thong	Tha Chin	0.55	-	-	0.55	1.0%	0.3%

In addition, each LAO should strictly enforce regulations that require households, markets, businesses and all other organizations in their area to separate their waste at source.

Establish a process of participation by local residents in giving recommendations, making decisions and cooperating in the implementation of management projects. Manage solid waste and hazardous waste from the beginning. This will reduce conflicts and opposition from the people.

The study results indicate that by eliminating the exposed MPW from the top 10 most critical districts from the priority catchments, the amount of MPW discharged into the marine environment from the priority catchments will reduce significantly, potentially by about 50 percent. Prioritizing the top three most critical districts may reduce the discharge of MPW into the marine environment by about 25 percent.

4.3 RECOMMENDATIONS TO IMPROVE THE DATA AND UNDERLYING MODELS

The results of the assessment are based on limited data and developing knowledge. In this section, recommendations are provided to improve the data and knowledge. Further details are provided in Appendix F.

As the SWM data provides the basis to estimate exposed MPW, it is recommended to first improve SWM data before considering improving the other models. Recommendations to improve this data could include (see Appendix F for more details):

- Increase systematic sampling of SWG and waste composition at the LAO or subdistrict levels.

- Undertake field studies to assess the material recovery factor for residential waste pickers.

- Include a specific SWM question in the NSO annual survey module—for example, one that targets the frequency of waste handling practices.

- Require recycling shops to provide a detailed overview of the amounts of the various types of waste that arrive at the locations and their individual recycling rate.

- Require a daily log to be kept at disposal facilities of how much solid waste arrives at the facility and where each truck comes from.

- Monitor the area around controlled dumps and open dumpsites to detect leakage of (plastic) waste.

Once better SWM data and an improved SWM model is available, evaluate whether improving the hydrological models to the described level of detail is required and will provide the necessary additional information to inform policy. The available hydrological information was incomplete for some catchments and all the tourist hotspots (the islands and Krabi province). These data are used to estimate the runoff and discharge and provide estimates to calculate wash-off of exposed MPW. If it is needed, recommendations to improve the hydrological data include (see Appendix F for more details):

- Start collecting hydrological data at the small islands and in the small catchments.

- Collect datasets that describe the water taken out of the rivers for irrigation and water levels in, and management schemes of, reservoirs.

Lastly, modeling of fate and transport of plastics in rivers is still in its infancy and presents a great number of challenges. Investigating plastic waste distribution along riverbanks, in the water column, in riverine sediment and so on could help to better understand how different riverine features (e.g, size, meandering, vegetation, soil) can affect the transport and retention of plastic waste. More realistic parameters of retention could be defined. These are, nevertheless, research questions that need to be addressed through scientific investigation and the larger scientific community. As new knowledge on riverine transport and fate becomes available, it can then be incorporated in the calibration of the transport modeling parameters. However, in the meantime, it is recommended to couple continuous and ongoing clean-up operations in certain rivers (for example, trash racks, clean-up initiatives being developed at the river mouth) with monitoring the amounts and composition of plastic waste intercepted in the river (see Appendix F for more details).

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