East Asia and Pacific Region: **MARINE PLASTICS SERIES**

Appendices

PLASTIC WASTE MATERIAL FLOW ANALYSIS FOR THAILAND

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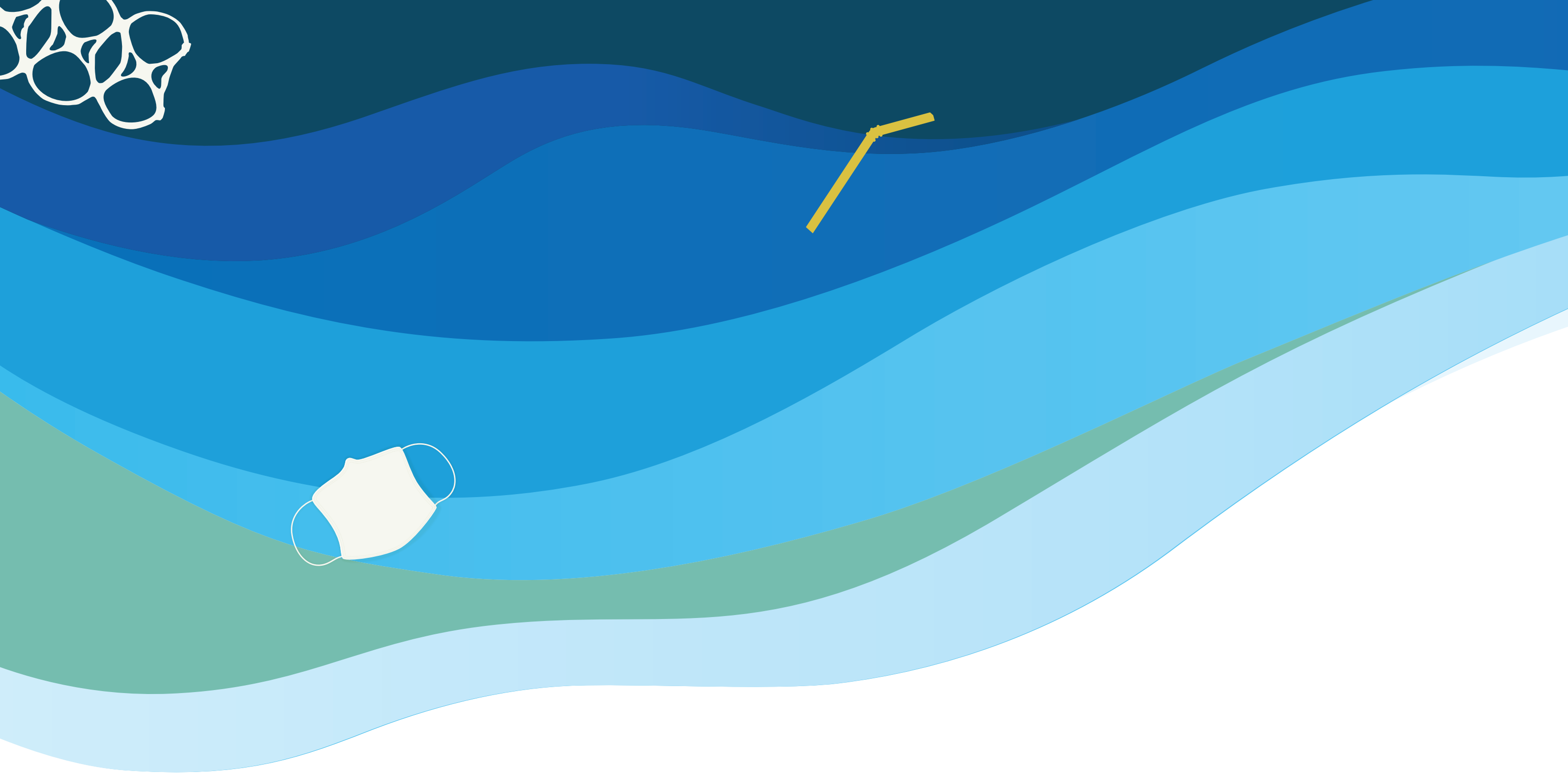

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CONTENTS

APPENDIX A.

PREVIOUS STUDIES ON PLASTIC MFA IN THAILAND

In Thailand, there are three main research studies on MFA of plastic, including:

1. Study from Sirindhorn International Institute of Technology, Thammasat University (Bureecam et al. 2017) (database in year 2013).
2. Study from Chulalongkorn University and Plastics Institute of Thailand (2018).
3. Study from Kasetsart University.

The studies conducted previously did not incorporate hydrology and the studies were not temporally specific (they do not show variations in waste generation throughout the year) and so do not provide insight into the seasonality of the plastic problem. The numbers from these studies cannot be used directly for validation of the current assessment. The studies either focused on a different physical region (for example, the coast) and/or did not include all potential sources for MPW (e.g., did not include uncollected waste). However, the insights gained from these studies were used in this assessment to set up the plastics MFA for Thailand.

Sirindhorn International Institute of Technology, Thammasat University

Bureecam et al. (2017) conducted an MFA of plastic in Thailand using data in 2013. The flow of plastic material started from the petrochemical industries, which produced 7,800 kton from virgin materials. The flow is composed of both raw materials that were from domestic and imported goods, meanwhile 1,100 kton were from domestic recycled materials. Plastic products were exported 2,100 kton, while 5,700 kton was domestically consumed.

The amount of plastic product consumption was 6,700 kton, consisting of 5,700 kton from domestic production and 1,100 kton from plastic products imported. As a result of the consumption, plastic waste generation was about 4,000 kton. About 3,500 kton of plastic waste were collected and transported to a disposal site by the local government. The remaining 770 kton of the plastic waste was recycled by the local government's staff and independent merchandisers. About 220 kton of plastic waste was incinerated to generate energy. The residual plastic waste of 1,900 kton was disposed of by landfilling. The rest of plastic waste were uncollected and inadequately disposed of.

Chulalongkorn University

The study using data based on 2017 has different results from the previous studies. According to the research of Chulalongkorn University and Plastics Institute of Thailand in 2018, total domestic resin production was 4,200 kton and total plastic production was 3,870 kton with plastic products in eight target products accounting for 1,900 kton. Total plastic waste from post consumers were 1,930 kton. About 1,900kton was properly managed waste: 1,510kton dumped into landfills and 390 kton recycled. According to the research, unmanaged accounted for only 30 kton and only 10–30 kton was likely to leak from the system to the ocean, together with the existing plastic waste in landfills.

Kasetsart University

The study from Kasetsart University shows the percentage of type of plastic waste in coastal areas in 2020. The study areas cover the coastal areas of the Gulf of Thailand from Trat to Prachuap Khiri Khan provinces based on the two major sources of plastic waste: plastic waste from 12 landfill sites in Bangkok and its perimeter and along coastal areas, as well as plastic waste deposited on the coast, excluding plastic waste submerged in sand or silt and plastic waste floating on the sea and sinking to the seabed. There were two types of Polyethylene (PE) plastics considered for the study, namely single-use plastics and multiple use plastics. About 50 percent of the consumption of PE plastics is single-use plastics. After being consumed, some of all types of PE plastics were reused or recycled and some became plastic waste. Some of the PE plastic waste was collected and disposed at landfill site (50 percent) and some leaked into rivers and canals. Approximately 14 percent of PE plastic waste was also found on the seashore.

APPENDIX B.

BASIC ADMINISTRATIVE INFORMATION FOR THE STUDY AREAS

PRIORITY CATCHMENTS

Phetchaburi Basin consists of 3 provinces, 113 subdistricts, total population of 3,471,592. Majority of people are in Phetchaburi, accounting for 86 percent of total population, of which 63 percent is in Subdistrict Organization Administration area and 28 percent is in Subdistrict Municipalities area. There are 18 subdistricts in Phetchaburi and Samut Songkham connected to the sea.

Mae Klong Basin consists of 11 provinces, 255 subdistricts, total population of 1,803,094. Majority of people are in Ratchburi, Kanchanaburi, and Nakhon Phatom, accounting for 41 percent, 33 percent, and 10 percent of total population, respectively, of which 46 percent is in Subdistrict Municipalities area and 38 percent is in Subdistrict Organization Administration area. There is 1 subdistrict in Samut Songkram connected to the sea in Mae Klong Basin.

Tha Chin Basin consists of 13 provinces and 378 subdistricts. Total population of 3,182,669 mainly lives in Samut Sakhon, Nakhon Pratom, and Supanburi provinces (32 percent, 25 percent, and 25 percent, respectively), of which 50 percent is in Subdistrict Organization Administration area and 38 percent is in Subdistrict Municipalities area. There are 10 subdistricts in Samut Sakhon and Samut Songkham connected to the sea.

Chao Phraya Basin consists of 16 provinces and 921 subdistricts, with total population of 15,953,521. Majority of people are in Bangkok, Samut Prakarn, and Nonthaburi, accounting for 53.5 percent, 10.9 percent and 10.3 percent of total population, respectively. There are in 6 subdistricts in Bangkok, Samut Prakarn, and Samut Sakhon connected to the sea.

Bang Pakong Basin consists of 11 provinces, 278 subdistricts, total population of 3,471,592. Majority of people are in Chachoengsao, Chonburi and Bangkok, accounting for 21 percent, 20 percent, and 19 percent of total population, respectively, of which 39 percent is in Subdistrict Municipalities area and 31 percent is in Subdistrict Organization Administration area. There are 6 subdistricts in Chachoengsao and Samut Prakarn connected to the sea.

TOURIST HOTSPOTS

Krabi has 31 subdistricts with total population of 178,767 in the study area and majority of people (81.73 percent) are in Subdistrict Administration Organization area.

Phuket has 17 subdistricts with total population of 703,618. Main population in Phuket lives in Subdistrict Municipality and Subdistrict Administration Organization area (53.42 percent and 23.64 percent).

Samui Island has 7 subdistricts and 1 City Municipality with total population of 42,023.

APPENDIX C.
DETAILED RESULTS

PRIORITY CATCHMENTS

Table C1.
MID-POINT ESTIMATES FOR (PLASTIC) WASTE GENERATION AND COLLECTION

SWM model results Plastic waste generation and collection	Priority Catchments					Total	Unit
	Phetchaburi	Mae Klong	Tha Chin	Chao Phraya	Bang Pakong		
Population	538,666	1,803,094	3,182,669	15,953,521	3,471,592	**24,949,543**	people
Solid waste per capita	1.086	1.088	0.936	1.320	1.081	**1.216**	kg/cap/day
Total solid waste generated	213.5	715.8	1,087.0	7,688.4	1,369.3	**11,074.1**	kton/year
Plastic content	17.30	17.27	17.27	17.40	17.33	**17.37**	%
Total plastic waste generated	36.9	123.6	187.7	1,337.7	237.3	**1,923.3**	kton/year
Plastic waste formally collected in catchment for disposal (in catchment or elsewhere)	16.8	54.9	85.2	866.2	137.4	**1,160.5**	kton/year
Plastic waste formally collected in catchment for recycling (in catchment or elsewhere)	12.5	51.0	59.7	375.0	49.8	**548.1**	kton/year
Plastic waste remains uncollected in catchment	7.7	17.7	42.7	96.5	50.1	**214.7**	kton/year

Table C2.
MID-POINT ESTIMATES FOR FINAL DESTINATION OF COLLECTED PLASTIC WASTE

SWM model results Plastic waste disposal and recycling	Priority Catchments					Total	Unit
	Phetchaburi	Mae Klong	Tha Chin	Chao Phraya	Bang Pakong		
Plastic waste processed (disposal or recycling) in catchment*	61.8	149.9	629.5	428.8	286.7	1,556.7	kton/year
Plastic waste disposed at formal disposal facilities in catchment*:	**32.0**	**26.0**	**502.8**	**291.6**	**242.0**	**1,094.3**	**kton/year**
in sanitary disposal facilities	6.0	3.0	432.3	223.8	169.2	834.3	kton/year
in controlled dumps	15.0	1.3	20.7	11.1	-	48.2	kton/year
in official open dumpsites	10.3	21.5	48.0	55.2	72.3	207.3	kton/year
in open burn locations	0.6	0.1	1.7	1.6	0.4	4.5	kton/year
Plastic waste recycled (official recycling facilities) in catchment*	**29.8**	**123.9**	**126.7**	**137.2**	**44.7**	**462.4**	**kton/year**
Destination of uncollected plastic waste:	**7.7**	**17.7**	**42.7**	**96.5**	**50.1**	**214.7**	**kton/year**
disposed on land (fly-tipping or terrestrial dumping)	0.3	1.5	6.1	7.9	12.3	28.1	kton/year
disposed into water	-	-	0.0	3.2	0.1	3.4	kton/year
openly burned	7.4	16.0	36.5	78.8	34.3	173.0	kton/year
other methods	-	0.2	0.1	6.6	3.4	10.2	kton/year

**The discrepancy between the plastic waste collected for disposal and recycling in a catchment and the plastic waste actually disposed or recycled in a catchment is due to several challenges: (1) misalignment between catchment and municipality boundaries; (2) irregularities in the data, and (3) possible unregulated waste import/export between municipalities.*

Table C3.
MID-POINT ESTIMATES FOR EXPOSED MPW (AVAILABLE FOR WASH-OFF)

SWM model results	Priority Catchments					Total	Unit
Mismanaged plastic waste and resulting plastic waste available for wash-off	Phetchaburi	Mae Klong	Tha Chin	Chao Phraya	Bang Pakong		
Mismanaged plastic waste:	**19.1**	**39.3**	**93.1**	**153.6**	**122.9**	**428.0**	**kton/year**
from controlled dumps	0.5	0.0	0.6	0.3	-	1.4	kton/year
from official open dumpsites	10.3	21.5	48.0	55.2	72.3	207.3	kton/year
from open burn locations	0.6	0.1	1.7	1.6	0.4	4.5	kton/year
from uncollected plastic waste	7.7	17.7	42.7	96.5	50.1	214.7	kton/year
Plastic waste available for wash-off:	**1.8**	**3.7**	**11.5**	**17.0**	**19.6**	**53.6**	**kton/year**
from sanitary disposal facilities	-	-	-	-	-	-	kton/year
from controlled dumps	0.5	0.0	0.6	0.3	-	1.4	kton/year
from official open dumpsites	1.0	2.1	4.8	5.5	7.2	20.7	kton/year
from open burn locations	-	-	-	-	-	-	kton/year
from recycling (official recycling locations)	-	-	-	-	-	-	kton/year
from uncollected plastic waste	0.3	1.5	6.1	11.2	12.4	31.5	kton/year
from disposal on land (fly-tipping)	0.28	1.5	6.1	7.9	12.3	28.1	kton/year
from disposal to water	-	-	0.0	3.2	0.1	3.4	kton/year
from openly burned	-	-	-	-	-	-	kton/year
from buried in terrestrial environment	-	-	-	-	-	-	kton/year

Table C4.
MID-POINT ESTIMATES FOR FATE AND TRANSPORT IN THE ENVIRONMENT FOR EXPOSED MPW

DELWAQ model results	Priority Catchments					Total*	Unit
	Phetchaburi	Mae Klong	Tha Chin	Chao Phraya	Bang Pakong		
Final destination (from terrestrial environment):							**kton/year**
weathered and/or retained in soils	1.17	*1.49*	9.94	6.63	9.96	27.71	kton/year
washed-off to and directly disposed in rivers	0.09	*0.13*	7.05	7.62	4.78	19.53	kton/year
Final destination (once in riverine environment):	**0.09**	***0.13***	**7.04**	**7.62**	**4.78**	**19.53**	**kton/year**
captured behind dams	-	*0.01*	0.00	0.24	-	0.24	kton/year
buried or stored in river	0.04	*0.08*	3.04	4.20	3.00	10.29	kton/year
total discharged into marine environment	0.04	*0.06*	4.01	3.45	1.80	9.30	kton/year
Total discharged into marine environment from rivers	**0.04**	***0.06***	**4.01**	**3.45**	**1.80**	**9.30**	**kton/year**

**Uncertainties in the DELWAQ modeling for the Mae Klong catchment mean that it has been excluded from estimated totals*

TOURIST HOTSPOTS

Table C5.
MID-POINT ESTIMATES FOR (PLASTIC) WASTE GENERATION AND COLLECTION

SWM model results Plastic waste generation and collection	Priority Tourist Hotspots Krabi	 Phuket	 Ko Samui	Total	Unit
Permanent residents	178,767	703,618	42,023	**924,407**	people
Tourists (average number of tourists per day)	51,768	156,335	37,961	**246,064**	people
Population (residents and tourists)	230,534	859,953	79,984	**1,170,472**	people
Solid waste per capita	1.005	0.855	0.993	**0.894**	kg/cap/day
Total solid waste generated	84.5	268.4	29.0	**381.9**	kton/year
Plastic content	17.30	17.24	17.00	**17.23**	%
Total plastic waste generated	14.6	46.3	4.9	**65.8**	kton/year
Plastic waste formally collected	9.1	36.3	4.2	**49.6**	kton/year
Plastic waste recycled	4.5	4.0	0.8	**9.3**	kton/year
Plastic waste remains uncollected	1.0	5.9	-	**6.9**	kton/year

Table C6.
MID-POINT ESTIMATES FOR FINAL DESTINATION OF COLLECTED SOLID AND PLASTIC WASTE[1]

SWM model results Plastic waste disposal and recycling	Priority Tourist Hotspots Krabi	 Phuket	 Ko Samui	Total	Unit
Plastic waste processed (disposal or recycling) on island*	23.3	46.2	9.7	79.3	kton/year
Plastic waste disposed at formal disposal facilities in catchment*:	**11.6**	**44.1**	**8.4**	**64.0**	**kton/year**
in sanitary disposal facilities	8.7	44.1	-	52.8	kton/year
in controlled dumps	-	-	-	-	kton/year
in official open dumpsites	2.8	-	8.4	11.2	kton/year
in open burn locations	-	-	-	-	kton/year
Plastic waste recycled (official recycling facilities) in catchment*	**11.8**	**2.1**	**1.4**	**15.3**	**kton/year**
Destination of uncollected plastic waste:	**1.0**	**5.9**	**-**	**6.9**	**kton/year**
disposed on land (fly-tipping or terrestrial dumping)	0.0	0.5	-	0.5	kton/year
disposed into water	-	-	-	-	kton/year
openly burned	1.0	5.4	-	6.4	kton/year
other methods	0.0	-	-	0.0	kton/year

**The discrepancy between the plastic waste collected for disposal and recycling in a tourist hotspot and the plastic waste actually disposed or recycled in a in a tourist hotspot is due to several challenges: (1) misalignment between catchment and municipality boundaries; (2) irregularities in the data, and (3) possible unregulated waste import/export between municipalities/sub-districts.*

1 Note that currently in Ko Samui, all collected waste is wrapped and transported to the mainland for final disposal.

Table C7.
MID-POINT ESTIMATES FOR EXPOSED MPW[2]

SWM model results Mismanaged plastic waste and resulting plastic waste available for wash-off	Priority Tourist Hotspots			Total	Unit
	Krabi	Phuket	Ko Samui		
Mismanaged plastic waste:	**2.5**	**5.9**	**8.4**	**16.8**	**kton/year**
from controlled dumps	-	-	-	-	kton/year
from official open dumpsites	1.5	-	8.4	9.9	kton/year
from open burn locations	-	-	-	-	kton/year
from uncollected plastic waste	1.0	5.9	-	6.9	kton/year
Plastic waste available for wash-off:	**0.2**	**0.5**	**0.8**	**1.5**	**kton/year**
from sanitary disposal facilities	-	-	-	-	kton/year
from controlled dumps	-	-	-	-	kton/year
from official open dumpsites	0.2	-	0.8	1.0	kton/year
from open burn locations	-	-	-	-	kton/year
from recycling (official recycling locations)	-	-	-	-	kton/year
from uncollected plastic waste	0.0	0.5	-	0.5	kton/year
from disposal on land (fly-tipping)	0.0	0.5	-	0.5	kton/year
from disposal to water	-	-	-	-	kton/year
from openly burned	-	-	-	-	kton/year
from buried in terrestrial environment	-	-	-	-	kton/year

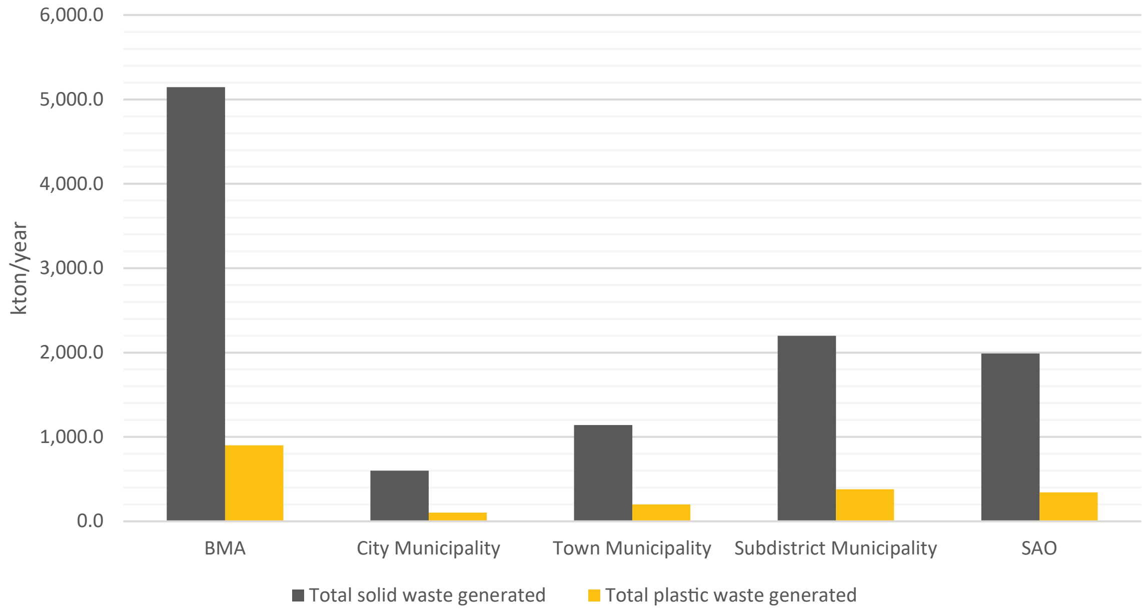
2 Note that currently in Ko Samui, all collected waste is wrapped and transported to the mainland for final disposal. Based on the available data (which include the presence of an open dumpsite on the island), the model indicates that no waste remains uncollected.

APPENDIX D.

HIGH PRIORITY CATCHMENT RESULTS BY LAO LEVEL

In Thailand solid waste management is organized through LAOs so it is relevant therefore to present detailed aggregated results for the high priority catchments at LAO type level. Figure D1 presents the total amounts of solid and plastic waste generated in the different LAO types. Clearly most solid and plastic waste is generated in BMA.

Figure D1.
DISTRIBUTION OF SOLID AND PLASTIC WASTE GENERATED THROUGH THE DIFFERENT TYPES OF MUNICIPALITIES

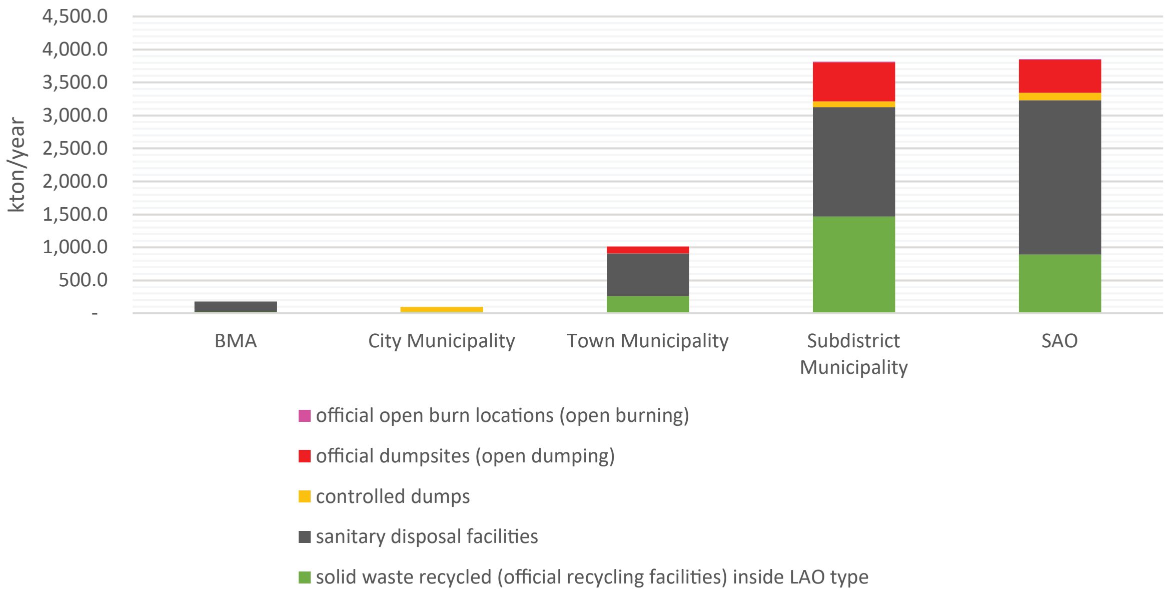


Source: Original calculations for this publication

Figure D2 presents the final destination of formally collected waste. This is based on both the reported amounts of collected waste and the actual location of the final disposal facilities. Although the cities and Bangkok in particular, generate a large amount of waste (Figure D2), most disposal facilities are situated outside cities in smaller subdistricts (Figure D3).

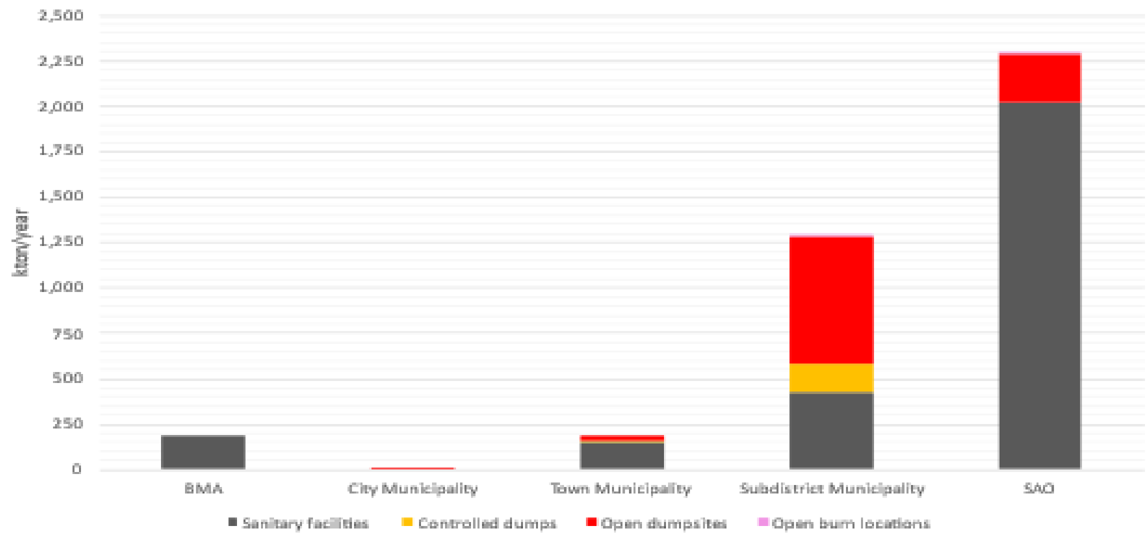
This is reflected in the high amounts of solid waste processed and disposed in the subdistrict municipalities and subdistrict administrative organizations (SAO). It is also here that most unsanitary disposal facilities—that may cause leakages of plastic waste—can be found, although the capacity of unsanitary disposal facilities is fairly low (Figure D4). The data and model results suggest that a large amount of solid waste is 'exported' from larger urban areas to the rural (sub)districts.

Figure D2.
DISTRIBUTION OF FINAL DESTINATION OF COLLECTED SOLID WASTE



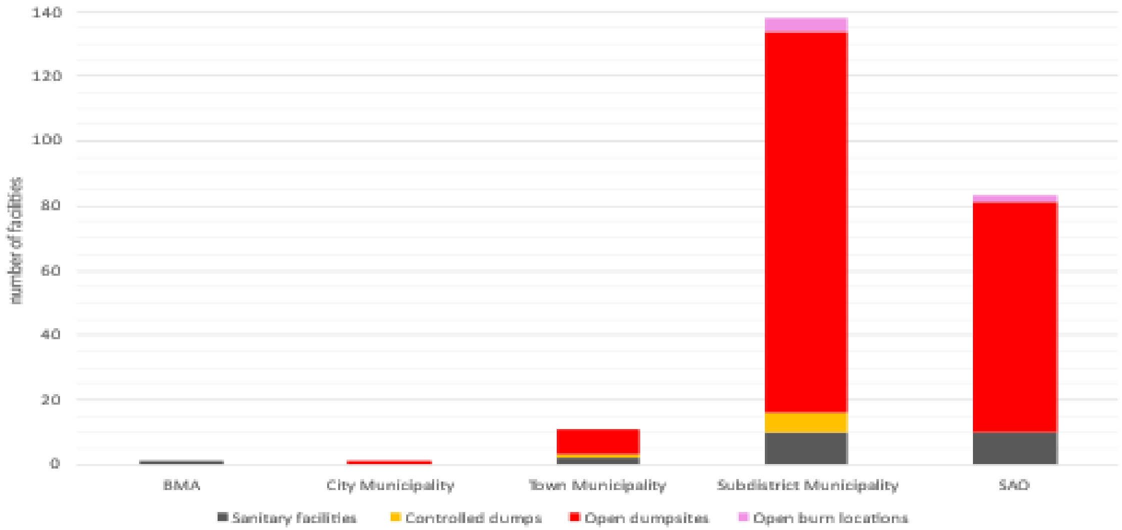
(Original calculations for this publication)

Figure D3.
DISTRIBUTION OF FORMAL DISPOSAL CAPACITY IN THE HIGH-PRIORITY CATCHMENTS



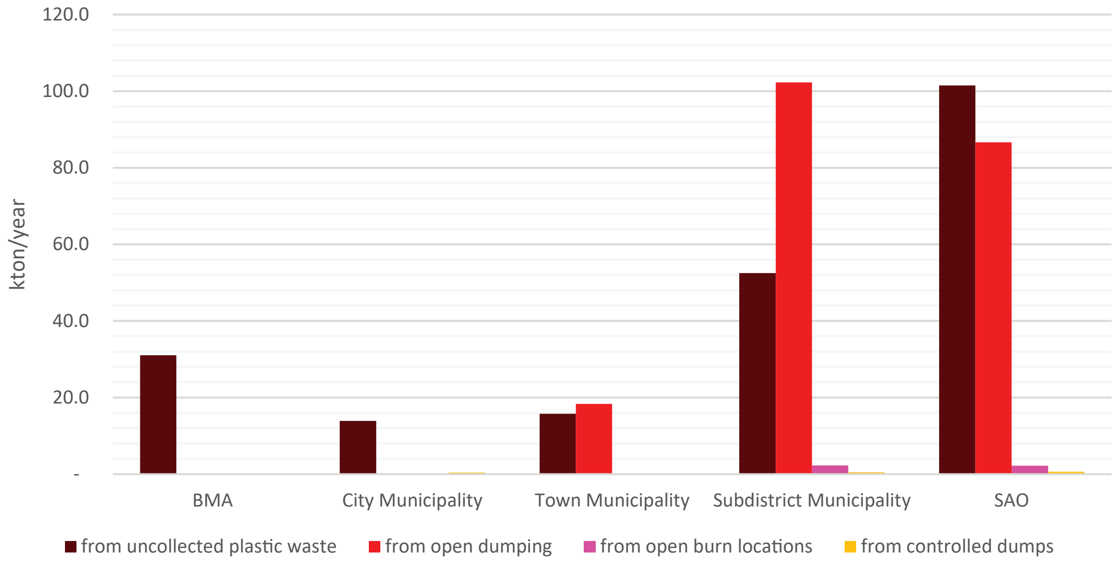
(Original calculations for this publication)

Figure D4.
DISTRIBUTION OF FORMAL DISPOSAL FACILITIES IN THE HIGH-PRIORITY CATCHMENTS



(Original calculations for this publication)

Figure D5.
MAIN SOURCES AND PATHWAYS FOR MISMANAGED PLASTIC WASTE FOR THE DIFFERENT TYPES OF MUNICIPALITIES



(Original calculations for this publication)

Figure D5 presents the disaggregated sources of MPW per LAO type. It becomes clear that the source of most MPW is in the smaller more rural subdistricts. But even in the cities, a significant amount of plastic waste remains uncollected.

Figure D6 shows the distribution of MPW per capita between the different LAO types. This figure indicates that in the smaller more rural LAOs, MPW per capita is much higher than in the cities. This is a combined result from the large number of unsanitary disposal facilities that are present in the more rural subdistricts and LAOs (Figure D3 and Figure D4) and the lower formal collection rates in these rural subdistricts (Figure D5). As an example, waste that is collected in BMA, is disposed in the subdistricts outside BMA[3] and might end

3 Although the origin of disposed waste is unknown, the capacity of the disposal facilities within the BMA is much smaller than the total amount of waste formally collected and therefore has to be transported to the facilities in the surrounding subdistricts.

up in unsanitary disposal facilities there. Figure D6 may incorrectly suggest that the residents of the smaller LAOs would be to blame. However, the figure illustrates that elimination of marine debris cannot be achieved without addressing the issues in the rural LAO.

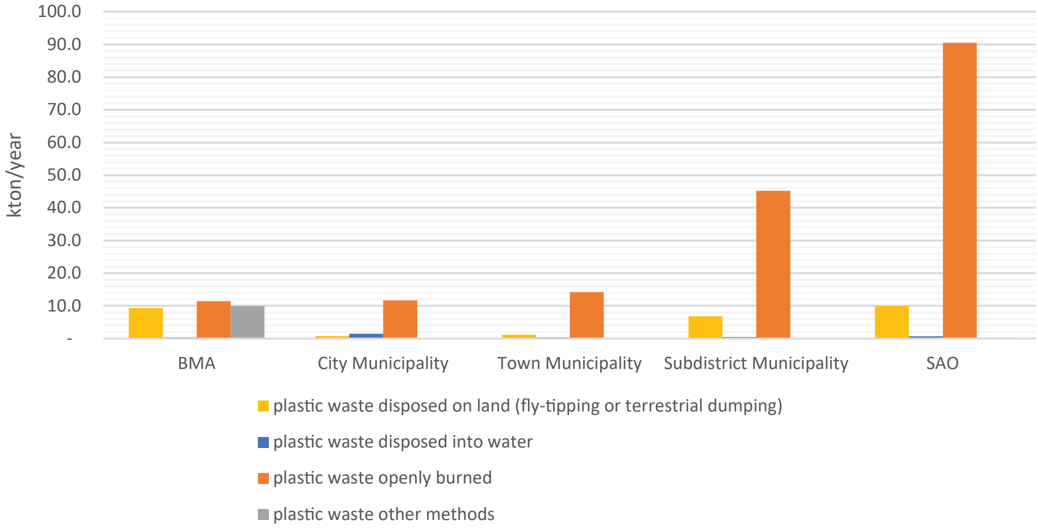
Figure D7 presents the estimated amounts of uncollected plastic waste that are handled in different ways (disposal on land, disposal to water, openly burned, or other methods). Clearly open burning is the most common waste handling practice in general, but it is much more prevalent in the smaller LAOs than it is in the 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 the rural areas (assuming subdistrict municipalities and SAOs are mostly rural municipalities) (Figure D8). Similarly, the results suggest that fly-tipping is slightly more common than disposal in water in the more rural areas. Nevertheless, open burning of uncollected waste is a method generally practiced everywhere, although slightly more common in the rural areas. But still, the results suggest that slightly more than half of the uncollected waste in Bangkok is openly burned (calculation is based on NSO's survey percentage).

Figure D6.
DISTRIBUTION OF MPW PER CAPITA PER YEAR OVER THE DIFFERENT TYPES OF MUNICIPALITIES

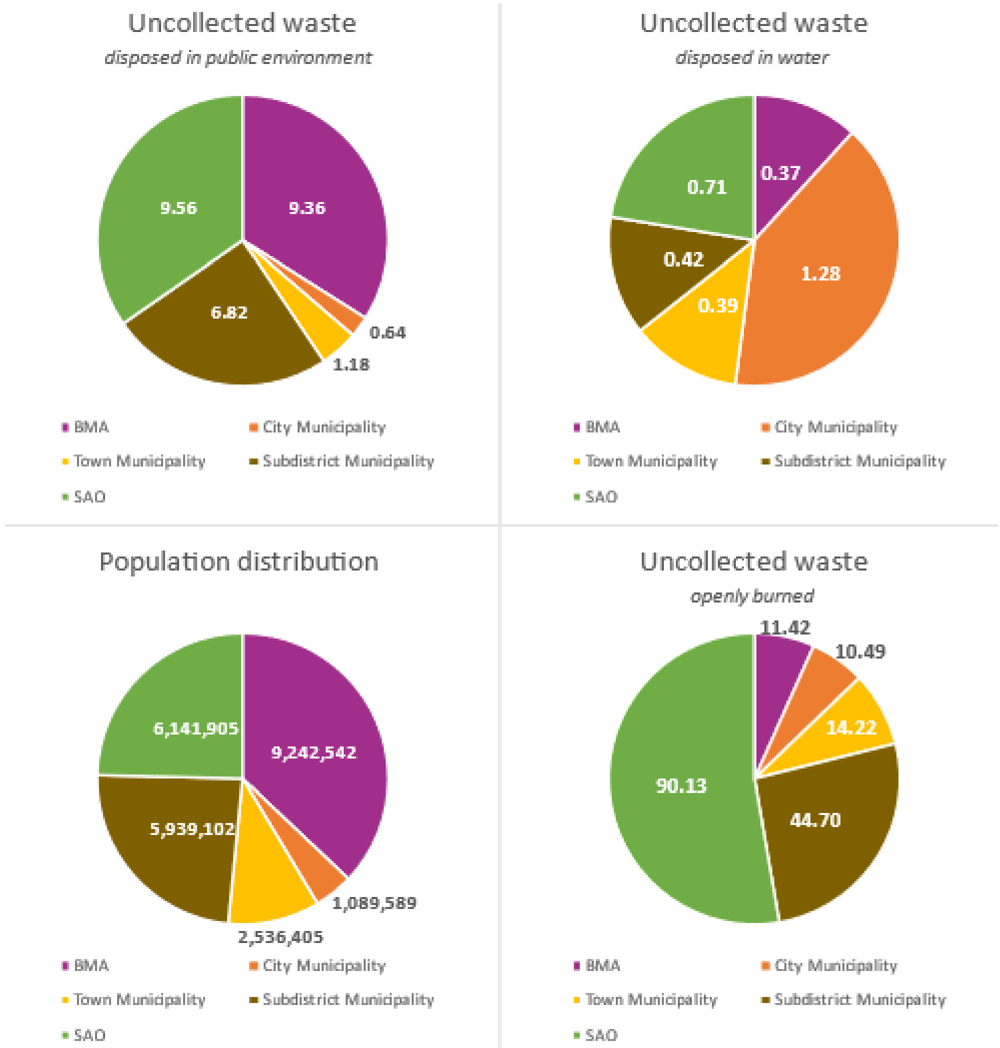
(Original calculations for this publication)

Figure D7.
DESTINATION OF UNCOLLECTED PLASTIC WASTE (BASED ON NSO'S SURVEY PERCENTAGE)



(Original calculations for this publication)

Figure D8.
POPULATION DISTRIBUTION (BOTTOM LEFT FIGURE, LABELS IN NUMBER OF PEOPLE) AND DISTRIBUTION OF DESTINATION OF EXPOSED UNCOLLECTED PLASTIC WASTE BASED ON NSO'S SURVEY PERCENTAGE (LABELS IN KTON/YEAR)



(Original calculations for this publication)

APPENDIX E.
DETAILED VALIDATION OF THE RESULTS

SWM MODEL

Validation of solid waste generation

The SWM model results indicate that in the high-priority catchments, in total, approximately 11,100 kton of municipal waste is generated annually (mid-point estimate). The range for these high-priority catchments is between 8,740 and 14,110 kton of solid waste per year. The high-priority catchments cover about 37 percent of the Thai population. Extrapolated to the whole population, the mid-point estimate for total SWG would be in the order of 30,200 kton/year.

Michikazu Kojima (2019) reported that, based on PCD data, Thailand produced 26,850 kton of municipal solid waste (year unknown). PCD reported this amount of solid waste generation for 2015.

With Bangkok (where solid waste generation per capita is considered significantly higher than average in Thailand) included in the high-priority catchments, it is concluded that the SWM model results are a realistic estimate.

Validation of plastic content

On average, the plastic content is about 17.4 percent in the high-priority catchments. The high plastic content is consistent with the plastic content reported by and observed in other countries in the region.

Although the range (14.4–21.0 percent) is wide, it reflects the limited data available at LAO and subdistrict levels. The plastic content is also considerably higher than the 12 percent that was assumed by Jambeck et al. (2015) in 2010. It must be noted that PCD itself reported in 2004 an average plastic content of about 17.3 percent in Thailand[4] (which is used for the mid scenario).

It is concluded that the estimated plastic content is a realistic estimate.

In this analysis it is assumed that the plastic content remains constant during each step in the MFA. Although practices such as recycling are likely to change the plastic content during the flow of waste from source to final destination, there are currently no data to quantify this and differentiate plastic content during each step in the material flow model.

Validation of formal collection and recycling

The available data do not allow for verification of the reported volumes of solid and plastic waste formally collected and recycled. At the district level, this may lead to underestimations of uncollected waste and this may explain the model results for Ko Samui where the model indicates that all waste is formally collected.

In this study, it is assumed that no solid waste is collected outside of an LAO/subdistrict. Waste that arrives at a formal disposal facility may have been collected in another LAO or subdistrict. However, the available data do not contain information to backtrack where collected waste originates from. In the model, formally collected waste is distributed over all known active formal disposal facilities within that province. At the (sub) district level this may lead to a net 'import/export' of waste.

In this study, results are reported per catchment and therefore the actual location of the disposal facilities is important. Administrative areas—LAOs and (sub)districts—do not necessarily follow the same physical borders as catchments. Therefore, some waste may be 'imported/exported' into/out of the catchment, although no import/export of waste may take place.

4 Derived from PCD reports including manual for conducting feasibility study of integrated solid waste management facility for LAOs (2019) and National Survey and Analysis of Solid Waste Composition (2004).

The model results indicate a recycling rate of about 28.1 percent in the high-priority catchments. This is roughly in line with a reported recycling rate of 26.5 percent in 2017.[5] However, this rate is likely based on the same database and may not be considered an independent verification, the results do seem at least in line with PCD's own estimates. For the tourist hotspots, the recycling rate is significantly lower than in the high-priority areas and is estimated at only about 13.6 percent.

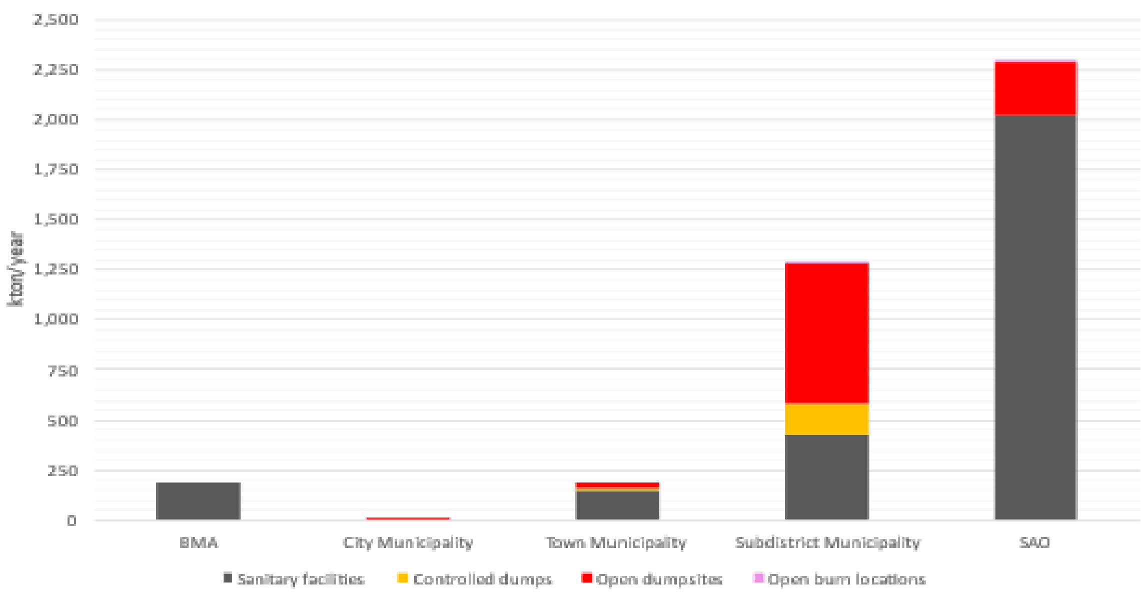
The NSO household survey (NSO 2019) is a good basis to validate formal collection rates. The NSO household survey indicates that the combined formal collection and recycling rate in the provinces in high-priority catchments is about 84.8 percent. The United Nations Environment Programme (UNEP 2017) reports a formal collection rate of 76.23 percent in the whole of Thailand. The model results indicate a mid-point estimate for combined formal collection and recycling of 89.9 percent (range 74.0–96.6 percent).

The modelled collection rates are high compared to the collected rates as reported in the international literature. However, considering that since the rates were reported, Thailand has invested to improve formal collection of solid waste, the rates are considered realistic. However, this also indicates that uncollected waste may be underestimated in the low-end scenario but seem realistic in the mid and high-end scenarios.

Validation of mismanaged plastic waste (MPW)

The distribution of MPW from unsanitary disposal facilities and uncollected waste is considered realistic. From the available data, it becomes clear that although the total installed capacity at sanitary disposal facilities is high (Figure E1), the number of open dumpsites remains high especially in the smaller LAO (subdistrict municipalities and SAO) and so the more rural areas (Figure E2). It is also these areas where collection rates are relatively low, leaving a relatively large proportion of generated solid waste uncollected.

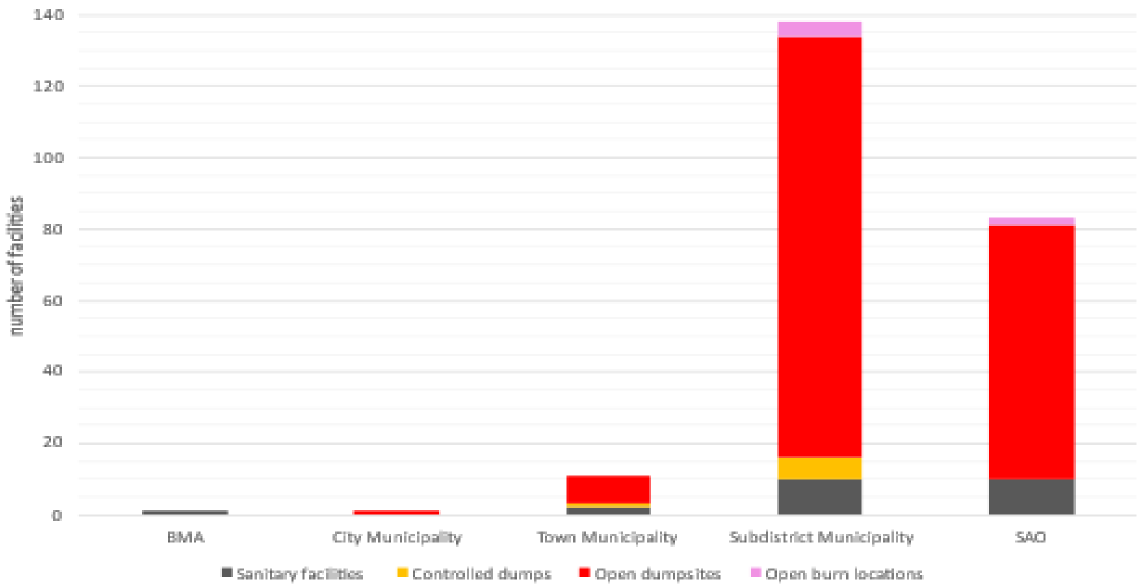
Figure E1.
INSTALLED FORMAL DISPOSAL CAPACITY PER LAO TYPE IN THE HIGH-PRIORITY CATCHMENTS AND TOURIST HOTSPOTS



(Original calculations for this publication)

5 Obtained from: Ninth Regional 3R Forum in Asia and the Pacific, 2019 (https://www.uncrd.or.jp/content/documents/7538Combined-front%20 page+report-Thailand.pdf).

Figure E2.
NUMBER OF VARIOUS TYPES OF DISPOSAL FACILITIES PER LAO TYPE IN THE HIGH-PRIORITY CATCHMENTS AND TOURIST HOTSPOTS



(Original calculations for this publication)

There are no other datasets available and no studies available to verify these results. It is therefore not possible to validate these results and compare these with national surveys or other studies. Cross-validating these findings would theoretically be possible by creating a different cross-section from the NSO national survey dataset.[6] However, this was not possible within this project.

It was not possible to verify the locations of the unsanitary disposal facilities.

HYDROLOGICAL MODELS

Validation of the hydrological model

The hydrological models that are developed as part of this study are used to translate rainfall into runoff and discharge. For the five high-priority catchments and for the three tourist hotspots, hydrological models were developed.

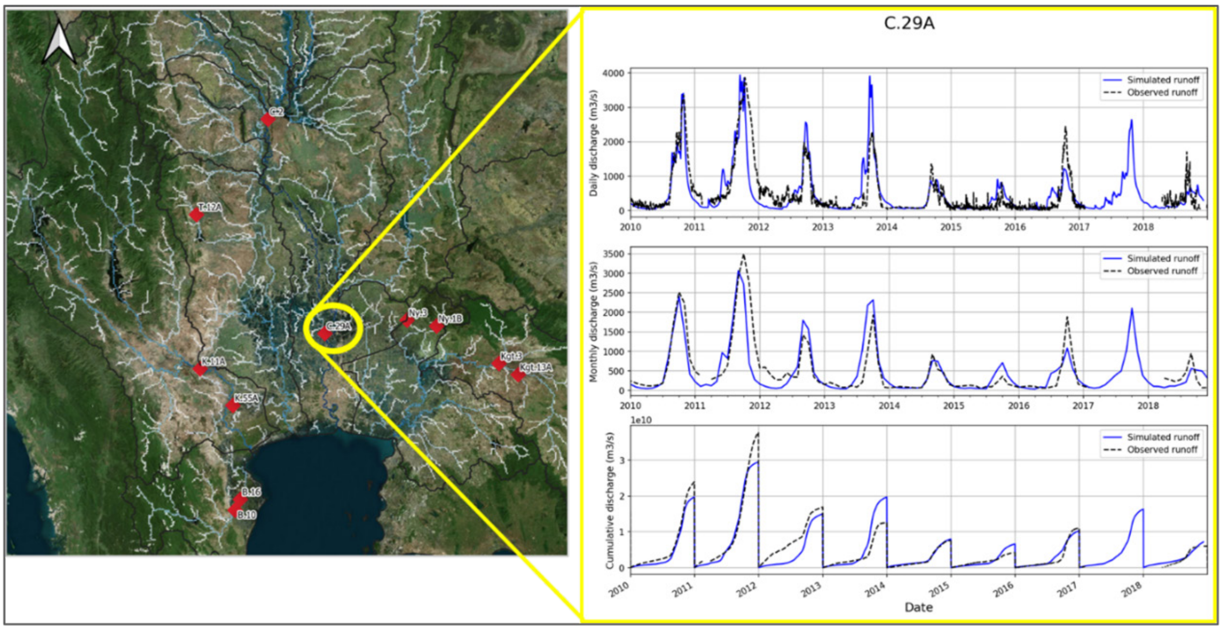
From Figure E3, it can be seen that the model for the Chao Phraya River is very well capable in capturing the discharges of the river during both the dry and wet seasons and is capable of capturing the seasonal variations. This is very important for simulating wash-off and plastic discharge correctly. The figure also shows that it is possible to simulate accurately dry and wet years, meaning that the order of wet and dry years is the same in the simulation as it is in the observations. Finally, it is shown that the model also simulates the cumulative volumes correctly.

In Figure E4 the climatology of the rainfall and evaporation is shown together with the discharge regime of the Chao Phraya. This figure shows a very good match between the simulated and observed values, meaning that the seasonal patterns are indeed perfectly captured with the model.

The performance indicator values (presented in Table E1) provide insight into how well the models are capable of representing the actual conditions. The results are very good for the largest catchment, the Chao Phraya catchment. For the Tha Chin and Bang Pakong catchments, the results are good. The model for the Phetchaburi is reasonable for high discharges but is underperforming during low-rainfall-low-discharge conditions.

6 The NSO household survey is reported per province. In principle, NSO knows the location of the interviewed households and therefore could do a cross-section across types of LAOs/subdistricts and report accordingly. It is recommended to take this into consideration.

Figure E3.
MODELING RESULTS FOR THE CHAO PHRAYA AT GATE C.29



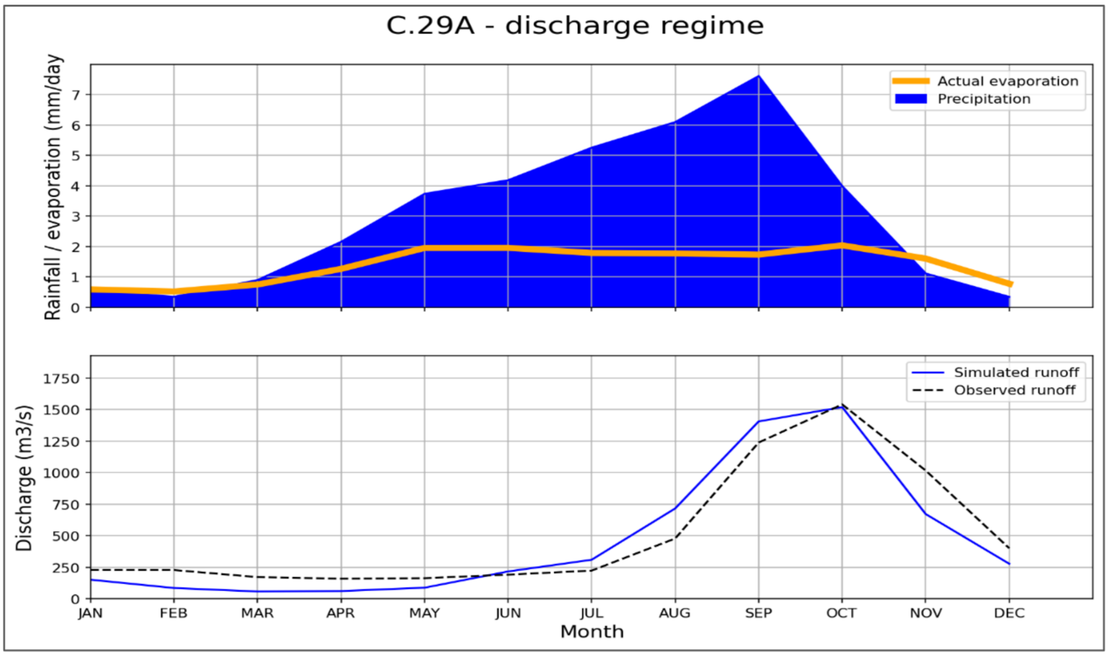
(Original calculations for this publication)

The model for the Mae Klong River is not performing well neither under low- nor high-rainfall conditions. The main reason for this is the complexity of the upstream reservoir system, which is not well captured in the model. The wflow_sbm model includes a simple reservoir module, but this module is insufficient for capturing the real dynamics of the reservoir operations in this catchment. To improve the model performance, it is therefore recommended that in the future for the Mae Klong a more detailed approach for the reservoir modeling is applied. By applying the improved reservoir module, including detailed information about the reservoir operations (rule-curves), the results can probably be improved considerably.

The same problems, albeit much less prominent, are shown in Phetchaburi catchment. The performance is not as good as the Chao Phraya model. Also, in the Phetchaburi basin an upstream reservoir seems to be causing the problem. Applying an improved reservoir module, fed with detailed information about the reservoirs (for example, rule curves), can probably improve the model results considerably in the future.

Next to the reservoir module, the models can still be improved by further calibration of the model parameters. Mainly the soil-related parameters can be further improved since these parameters are now derived from the coarse global soil maps.

Figure E4.
CLIMATOLOGY (TOP) AND DISCHARGE REGIME (BOTTOM) FOR THE CHAO PHRAYA AT STATION C.29



(Original calculations for this publication)

Table E1.
SUMMARY OF THE SKILL SCORES FOR THE DIFFERENT RIVER CATCHMENTS

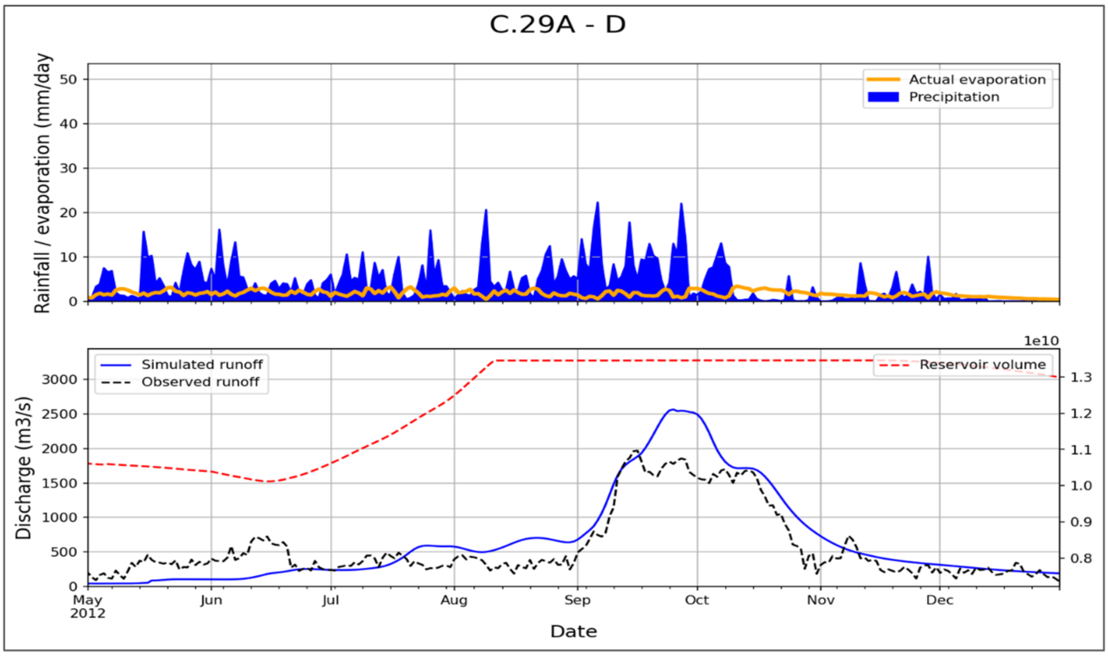
Location used for calibration	Phetchaburi (B.10)	Mae Klong (gate)	Tha Chin (T.12A)	Chao Phraya (C.29)	Bang Pakong (Kgt.3)
R2	0.42	0.49	0.59	0.83	0.84
RMSE	25.6	189.9	12.5	418.8	98.3
Nash-Sutcliffe	-0.01	-0.17	0.18	0.68	0.65
KGE	0.33	0.42	0.37	0.80	0.74

Effect of reservoirs

In the hydrological model, several reservoirs are included. These reservoirs are used to store water for irrigation and during peak flows. At the beginning of the wet season the reservoirs are normally relatively empty, creating enough space to store water during the peak. Once the rain starts, the reservoirs start filling up, while maintaining a steady and relatively low outflow. Only once the reservoirs are filled up, the water entering the reservoirs needs to be released. This effect is nicely demonstrated in Figure E5. Here it shows that the first rainfall starts filling up the reservoir (red line), while maintaining a steady discharge (outflow). Only once the reservoir volume reaches the maximum volume, the outflow of the reservoir increases, resulting in a peak discharge at gauge C.29.

Note: In the fate and transport model, it is assumed that dams and reservoirs trap 100 percent of incoming MPW.

Figure E5.
DETAIL OF THE HYDROGRAPH FOR THE CHAO PHRAYA AT GAUGE C.29. IN RED, THE RESERVOIR VOLUME FOR ONE OF THE LARGE UPSTREAM RESERVOIRS IS SHOWN



(Original calculations for this publication)

Coastal zones and small islands

No calibration and validation could be performed for the coastal zones and small island models, since no observed discharge data were available. For now, it is assumed that all parameters linked to land use and soil properties are the same as for the mainland catchments. However, since land use and soil data are grid based the actual values of the parameters do differ, since different land use and soil classes are found on the islands, compared to the mainland catchments. There are some considerations to make, that might provide some insight into how the models can be improved in the future.

- The coastal zones and small islands are relatively steep catchments and differ from the mainland catchments. This could be a reason to differentiate the parameters for these models from the parameters used in mainland models. By changing certain parameters (for example, the hydrological connectivity of the soil), a different hydrological behavior (more direct runoff) can be achieved, resulting in higher and probably more realistic, plastic wash-off rates. However, given that no discharge observations are available, it is very difficult to determine the desired change to be made.
- The global land cover data does not show any built-up area in for some of the coastal zones and small islands. This is not realistic, since it is known that especially the zone close to the sea contains build-up area. Using a different, more detailed land cover map as input for the hydrological model could result in more direct runoff, resulting in higher (and probably more realistic) plastic wash-off.

FATE AND TRANSPORT MODELS

Validation of MPW discharges through field observations

Bangkok Metropolitan Administration

The BMA keeps a record of debris retrieved from the Chao Phraya River. Monthly average data for the period January 2017 to December 2019 were made available to validate the DELWAQ model results.

The BMA data relate to single monthly averages of retrieved debris. Reportedly, BMA retrieves debris from the Chao Phraya River from floating barges that are operated from about 08:00 a.m. to 05:00 p.m. daily; outside of the operating hours, debris is transported to the river mouth unrestricted.

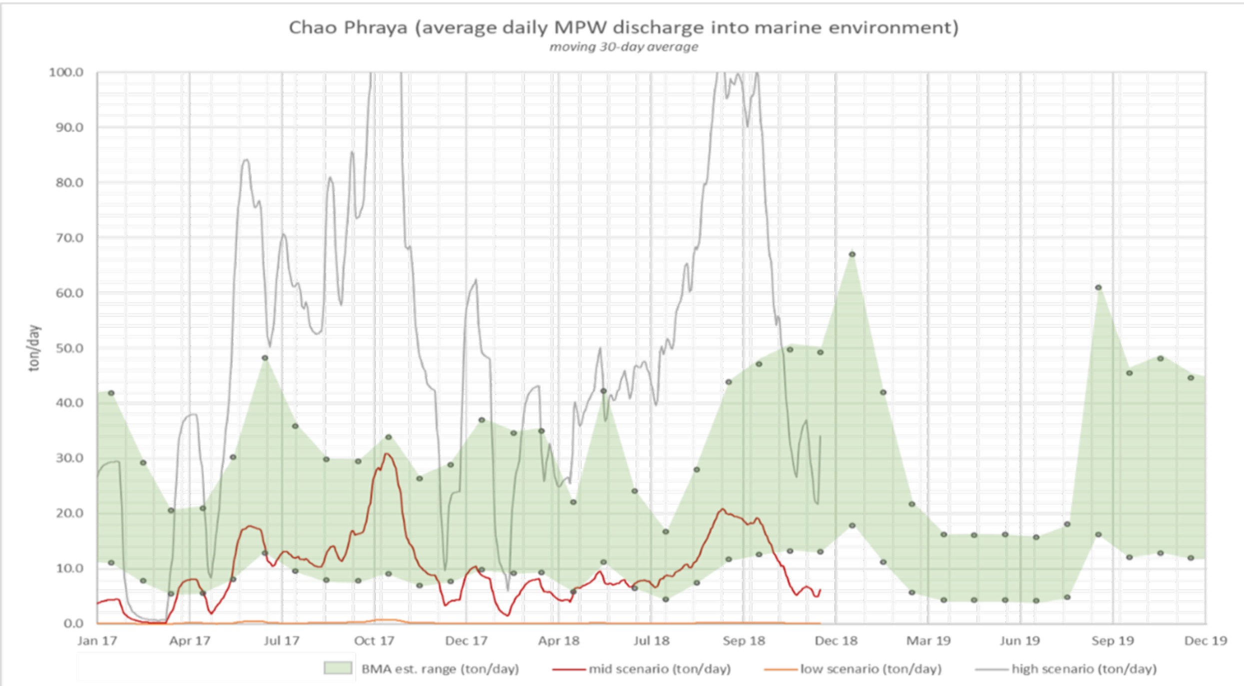
No data on specific plastic content for each data point are available,[7] although the 2019 data suggest that plastic content is on average at least 11 percent and about 27.5 percent when aquatic vegetation (water hyacinth and aquatic weed) is neglected. Observations with nets in the five catchments (by Department of Marine and Coastal Resources (DMCR), see next page) and elsewhere (for example, World Bank 2021) indicate that plastic content varies widely between the dry and wet seasons with observed ranges of 47–97 percent in a dry season and 31–83 percent in a wet season.

Only floating debris is retrieved, and the floating barges do not cover the entire width of the river, and likely do not retrieve all floating debris. In addition, a significant amount of plastic is transported below the water surface and not all floating debris will be visible. Therefore, it is likely that a significant part of floating plastic is not retrieved.

A range for plastic debris in the Chao Phraya River can be estimated based on the available data from BMA by assuming (a) that total debris outside of operating hours is in the same order, (b) plastic content is between 11 percent and 27.5 percent, and (c) between 30 percent and 50 percent of plastic debris is effectively retrieved. Based on these assumptions, for each month a range for plastic debris can be estimated.

Although the observations related to single monthly averages of retrieved debris and plastic content are very uncertain, the estimated range based on these data points show good correlation with the plastic discharges obtained by the model for this period including the general trend (Figure E6). The BMA data suggest that actual discharge of MPW might be in the upper range of the results.

Figure E6.
BMA MONTHLY AVERAGES FOR RETRIEVED WASTE (GREEN DOTS); DAILY DISCHARGE TIME SERIES DERIVED FROM THE MODEL (MID SCENARIO RED LINE, HIGH SCENARIO GREY LINE)



(Original calculations for this publication)

DMCR observations at high-priority river mouths

Theerawat Prempree et al. (2019), conducted regular measurements in the river mouths of the five main rivers that are also part of this study. Measurements were taken approximately every three months over a period from 2016 to 2019.

7 The provided data suggest that since 2019 plastic content is registered. However, the data were only provided for fiscal year 2019 and could not be used to further validate the model results.

Measurements were conducted by anchoring a net 5m wide and 2m deep, with a mesh size of 2 cm, in the channel far enough from the riverbank to ensure unobstructed flow and a minimum water depth of 2m. Samples were taken at high and low tide such that the flow rate, and consequently waste collection rate, varied depending on the tidal phase. A positive (downstream) flow rate was recorded for all samples, meaning they were not affected by upstream tidal flow which could displace waste from the net. For each observation sample, the mass of waste collected, duration of collection, and tidal phase were recorded. The compositional content of the waste collected was reported on a yearly total basis for all samples.[8] The plastic waste for each sample was calculated as the sum of hard plastic, film plastic, Styrofoam, and polymer fractions recorded for the sample year.

To compare the measurement data with the simulation results, some extrapolation of the raw data was required.

The samples were assumed to be taken over a width of 5m and from 0–2m below the water surface based on a textual description of the sampling method accompanying the data. It was assumed that the majority of plastic mass in the water column is concentrated at the surface. Therefore, the measured plastic mass was scaled by the river width[9] at mean sea level to obtain a total mass flow rate for the river to compare against the modelled results. The scaled observations are given in Table E2.

Table E2.
ESTIMATED TOTAL PLASTIC LOAD (BASED ON DATA FROM DMCR, INTERPOLATION TO ENTIRE RIVER BY DELTARES)

River		2016 plastic 13-14 Dec	plastic content	2017 total plastic debris [ton/day] 27-28 Mar	24-25 May	21-22 Aug	20-21 Nov	plastic content	2018 total plastic debris [ton/day] 27-28 Feb	11-12 Jun	22-23 Aug	04-05 Dec	plastic content	2019 total plastic debris [ton/day] 04-05 Mar	06-07 May	12-13 Aug
Phetchaburi	min	0.3	77.7%	0.2	0.3	0.1	3.4	90.5%	1.3	1.0	0.3	0.0	82.7%	0.4	0.2	1.1
	average	0.8		1.9	0.5	1.0	5.9		2.8	1.2	1.6	1.1		0.7	0.7	2.2
	max	1.4		5.3	1.0	2.1	8.4		5.6	1.6	2.9	3.5		0.9	1.7	3.3
Mae Klong	min	1.4	85.3%	0.1	0.2	4.1	6.1	98.6%	1.5	2.4	0.8	0.1	92.0%	3.5	1.4	4.8
	average	6.0		11.2	7.3	10.4	10.4		5.3	12.0	10.2	4.3		5.8	9.3	6.6
	max	12.8		26.4	18.2	15.4	13.4		11.9	26.8	19.5	13.4		9.7	22.7	8.5
Tha Chin	min	3.2	76.4%	7.7	4.6	10.8	7.5	94.3%	15.3	17.3	25.4	10.7	86.4%	0.9	0.9	2.2
	average	27.7		16.1	52.9	30.9	46.7		22.1	27.3	36.1	44.6		3.8	21.2	12.2
	max	54.3		29.3	148.5	50.2	90.5		28.0	46.9	46.9	103.0		7.3	36.4	22.2
Chao Phraya	min	43.9	93.8%	1.8	19.2	50.1	49.6	87.5%	168.4	1.8	7.2	4.4	82.3%	0.0	0.3	10.7
	average	113.9		122.8	121.7	196.6	167.8		177.3	26.9	31.7	141.9		9.6	15.7	16.3
	max	239.4		317.2	332.6	357.2	390.1		188.1	70.3	56.2	499.3		23.9	33.2	22.0
Bang Pakong	min	-	93.7%	0.0	0.1	1.5	3.8	77.5%	0.2	4.5	0.2	0.0	64.1%	0.3	0.3	11.8
	average	3.6		0.4	2.0	17.1	14.2		3.5	9.2	7.3	11.0		5.7	4.5	61.1
	max	12.4		1.3	4.9	26.4	32.9		7.5	17.1	14.4	37.4		11.5	11.5	110.5
Total	*min*	*48.8*	*year with*	*9.8*	*24.4*	*66.6*	*70.4*	*year with*	*186.6*	*27.0*	*33.9*	*15.1*	*year with*	*5.2*	*3.1*	*30.6*
	average	*151.9*	*very high*	*152.5*	*184.3*	*256.2*	*245.0*	*average*	*211.0*	*76.6*	*86.9*	*202.9*	*very low*	*25.7*	*51.5*	*98.5*
	max	*320.3*	*rainfall*	*379.5*	*505.1*	*451.2*	*535.4*	*rainfall*	*241.1*	*162.8*	*140.0*	*656.5*	*rainfall*	*53.4*	*105.5*	*166.4*

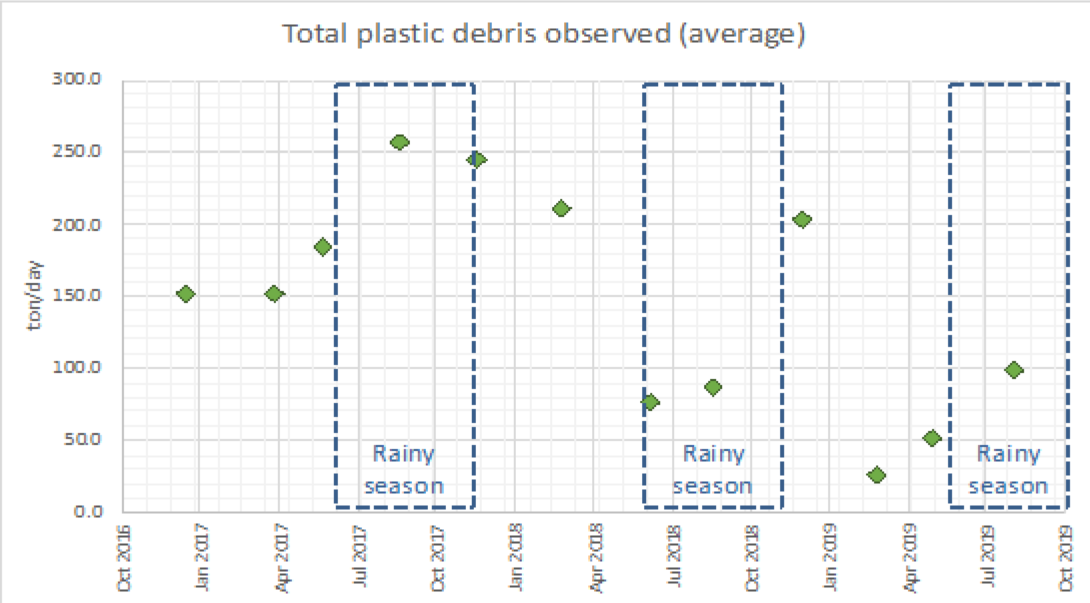
In Figure E8, the time series for plastic loads derived from modeling results are compared with the waste observations from DMCR. Noting that these observations are snapshots and therefore have limited representativeness of annual trends, if at all, they are in line with the observations from modeling that during wet years (2017) MPW discharges may be double from what they may be during a dry year (2019).

Plotting the total amount of plastic debris observations in the five rivers combined (Figure E7) show that during the dry season much larger individual discharges (for example, March 2018) have been observed than the lowest individual observations during the wet season (for example, August 2018). This further confirms that (brief) rainfall events mobilize accumulated exposed MPW and that rivers are the primary pathways for MPW to reach the marine environment.

8 Waste composition was reported as total mass of the following types: hard plastic, film plastic, fabric and fibre, Styrofoam, polymer, glass and ceramics, metal, paper, wood, and others.

9 Channel cross-sections provided by HII.

Figure E7.
TOTAL (AVERAGE ESTIMATED AMOUNT OF) PLASTIC WASTE OBSERVED (GREEN DIAMONDS) IN THE FIVE RIVERS



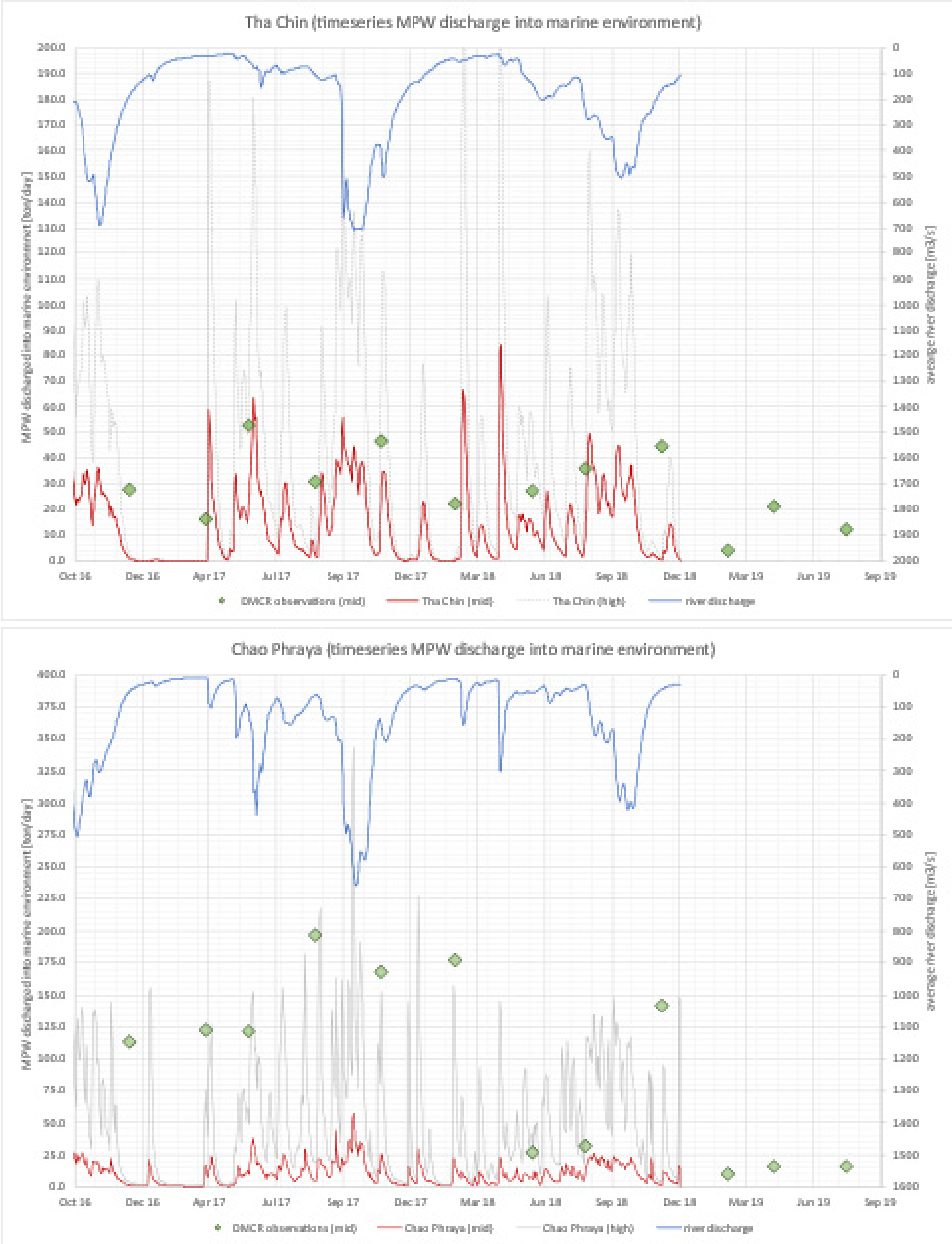
(Original calculations for this publication, data source: DMCR).

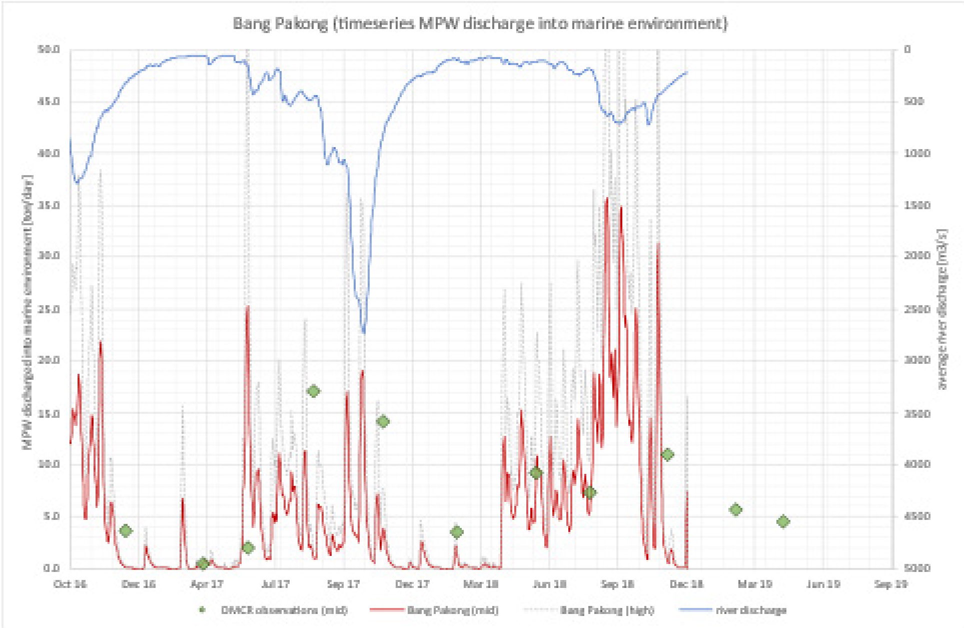
Catchments with well-performing hydrological models

Comparison of the simulation results with the field observations indicate that the models provide a good representation of plastic loads in the Tha Chin, Chao Phraya, and Bang Pakong rivers. The simulation results for the mid-point and high-end scenarios are in the same order of magnitude as the DMCR observations, while the low-end scenario clearly is an underestimation of expected plastic loads (therefore also not included in the graphs). The simulations were shown to also be capable of capturing hydrological events that were recorded in the measurements.

Figure E8.

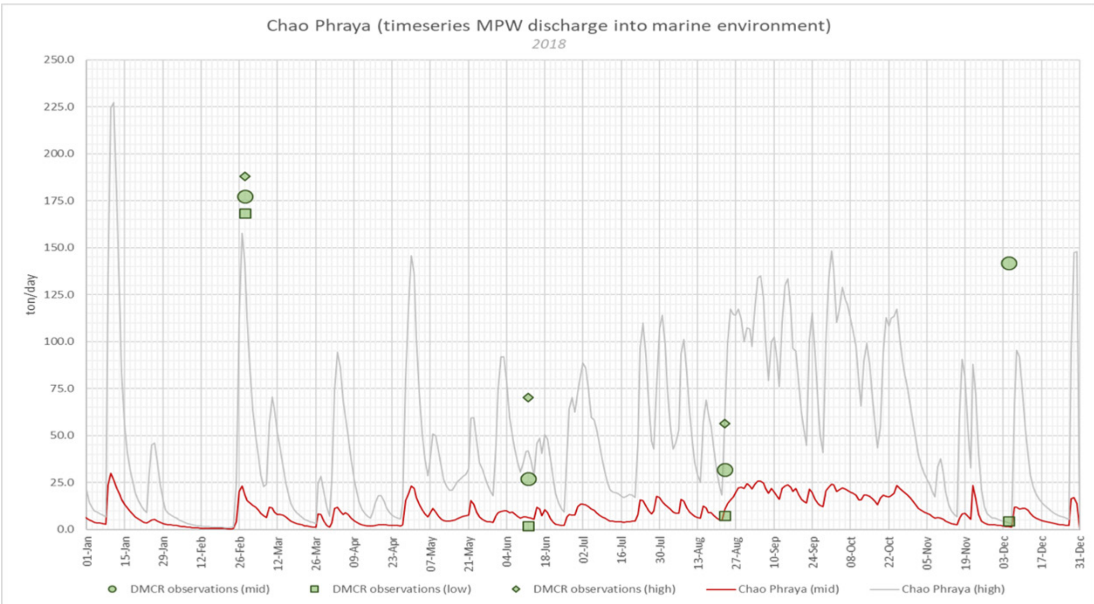
DMCR WASTE OBSERVATIONS (GREEN DIAMONDS) PLOTTED TOGETHER WITH DAILY DISCHARGE TIME SERIES DERIVED FROM MODEL RESULTS (MID-POINT SCENARIO IN RED, HIGH-END SCENARIO IN GREY), SHOW GOOD COMPARISON. BLUE LINES INDICATE AVERAGE DAILY RIVER DISCHARGES (REVERSE RIGHT AXIS). (FROM TOP DOWN: THA CHIN RIVER, CHAO PHRAYA RIVER AND BANG PAKONG RIVER.)





(Original calculations for this publication)

Figure E9.
DMCR WASTE OBSERVATIONS (GREEN DIAMONDS) PLOTTED TOGETHER WITH DAILY DISCHARGE TIME SERIES DERIVED FROM MODEL RESULTS (MID-POINT SCENARIO IN RED, HIGH-END SCENARIO IN GREY) FOR THE CHAO PHRAYA RIVER



(Original calculations for this publication)

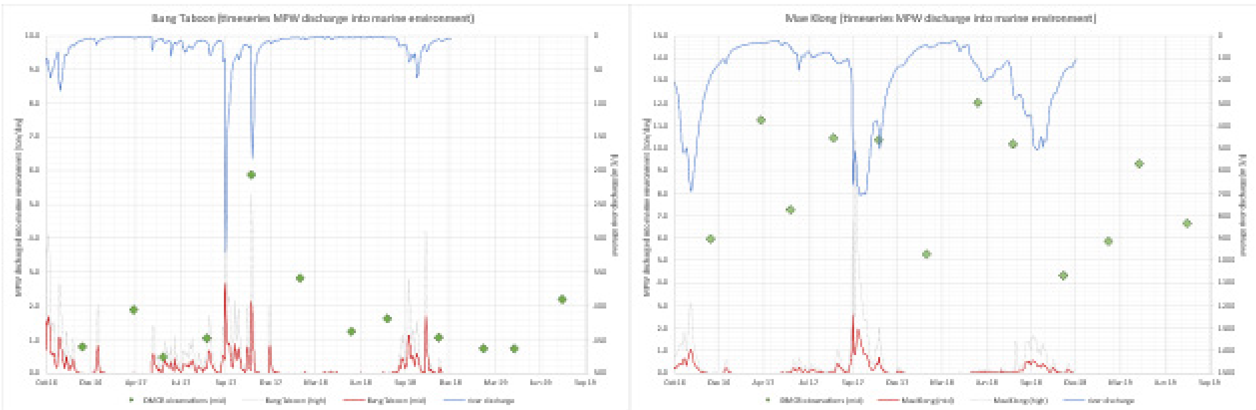
Figure E9 presents a closer look at the observations at the river mouth of the Chao Phraya River and the simulation results for the year 2018. The results show that when high plastic loads were observed in the field (March 27–28 and December 4–5, 2018), the model also indicates a high plastic load due to increased discharge caused by recent rainfall and wash-off. In June (11–12) and in August (22–23), low plastic loads were observed in the river, and the model also indicates lower plastic loads.

The observations on December 4–5 are especially interesting because the observation data show that there likely was a high discharge event that passed on that day. All estimated loads from the model simulations correspond well with the estimated observed loads.

Catchments with underperforming hydrological models

The models for the Phetchaburi and Mae Klong rivers perform less well. While the results for the Phetchaburi River match the measurements reasonably well during periods of higher river discharge, the results are underestimated during the dry season (Figure E10). The results for the Mae Klong River are much below observed plastic loads for both the dry and wet seasons. As stated earlier, the runoff and river discharge may be underestimated for these rivers, and it follows that the plastic mass flux is therefore also underestimated under the same conditions.

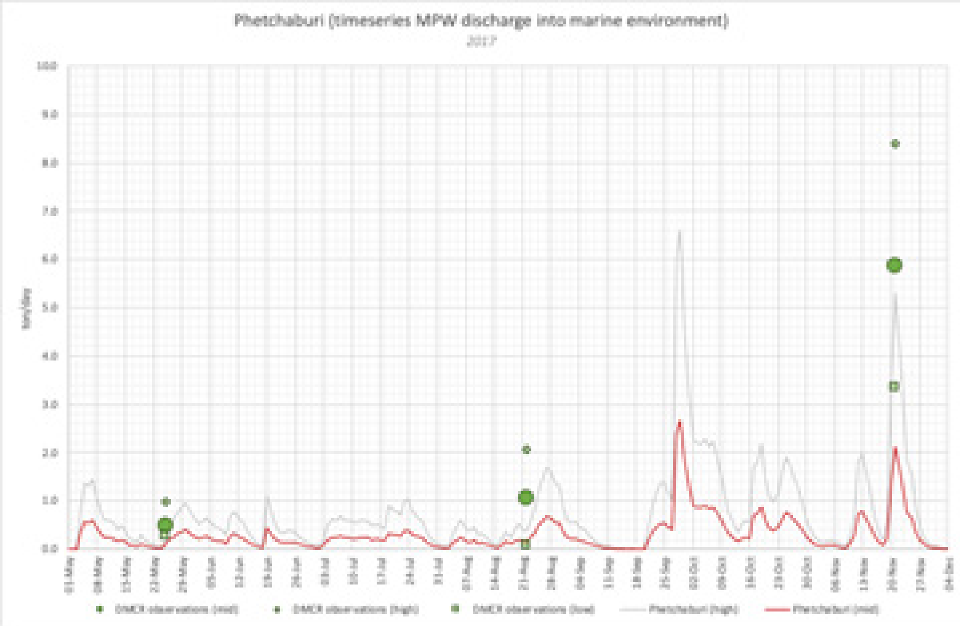
Figure E10.
DMCR WASTE OBSERVATIONS (GREEN DIAMONDS) PLOTTED TOGETHER WITH DAILY DISCHARGE TIME SERIES DERIVED FROM MODEL RESULTS (MID-POINT SCENARIO IN RED, HIGH-END SCENARIO IN GREY), SHOW GOOD COMPARISON. BLUE LINES INDICATE AVERAGE DAILY RIVER DISCHARGES (REVERSE RIGHT AXIS)



(Original calculations for this publication)

At the river mouth of the Phetchaburi River (Figure E11), the measurements from November 2017 were conducted around the time when rainfall had mobilized exposed MPW in the upstream catchment; the wider variability in the DMCR results indicates a wide variation of plastic load during that day. In May 2017 the simulated discharge is low for an extended period, which also corresponds with the narrow range in the debris observations.

Figure E11.
DMCR WASTE OBSERVATIONS (GREEN CIRCLES, DIAMONDS, AND SQUARES) PLOTTED TOGETHER WITH DAILY DISCHARGE TIME SERIES DERIVED FROM MODEL RESULTS (MID-POINT SCENARIO IN RED, HIGH-END SCENARIO IN GREY), AT THE RIVER MOUTH OF THE PHETCHABURI RIVER FROM MAY 2017 TO DECEMBER 2017



(Original calculations for this publication)

Tourist hotspots and small islands

The hydrological models for the tourist hotspots could not be validated and may significantly underestimate runoff and discharge. This has cascading effects on the fate and transport model results.

For the small islands, there are also no observation datasets available on washed-off (plastic) waste. It is therefore not possible to validate the model results of the fate and transport models for these domains. When we compare the wash-off rate for the small islands, with the wash-off rate of the high-priority catchments, it becomes apparent that the wash-off rates are very low (about 8.1 percent versus 39.2 percent). Without observation data, it is not possible to say why the rates are this low. It seems most likely due to underperforming hydrological models. Validation of the hydrological models based on new observation data is recommended.

It is possible that the models do not perform as well as the main catchments. A reason for this could be that the rainfall for these regions is over-, or more likely, underestimated. The rainfall data are rather coarse, and thus will average out the rainfall over a larger area, whereas in reality rainfall could be very localized, causing high-intensity local rainfall with high local wash-off rates. These events could contribute strongly to the total plastic discharge rates in these tourist hotspots.

Another reason could be that these regions are relatively steep compared to the mainland catchments. Therefore, the sub-surface flow rates are higher since they do depend on the slope of the catchments. The result is that water is drained quicker via the sub-surface, creating more space for storage of water in the sub-surface and thus less direct surface runoff.

When we calculate exposed MPW and MPW discharged into the marine environment in per capita, it also becomes clear that although exposed MPW is in the same order in the small islands as in the bigger catchments, the amount of MPW discharged into the marine environment is almost a factor 10 lower. This is further indication that the hydrological model is likely underperforming.

APPENDIX F.

DETAILED RECOMMENDATIONS TO IMPROVE DATA AND MODELING

RECOMMENDATIONS FOR IMPROVING ASSESSMENT OF PLASTIC WASTE FLOW AND LEAKAGES FROM LAND-BASED SOURCES

In this section, specific recommendations to improve the primary SWM datasets are provided. These are organized following the SWM modeling steps.

Indicator 1 - Total solid waste generated (population × solid waste/capita) and Indicator 2 - Total plastic waste generated (SWG × plastic content)

Accurate measurements of solid waste/capita and plastic content of waste are crucial to accurate assessment of PWG. Currently, there are no reliable data sources for either of these parameters at the LAO or subdistrict levels.

Recommended action: Increased systematic sampling of SWG and waste composition as part of routine activities (annually) of local authorities at the LAO or subdistrict levels. This would contribute to more reliable, locally relevant information for both the LAOs as well as improving the PCD database information.

Indicator 3 - Total plastic waste collected (formal + informal collection)

In Thailand, recycling is managed through recycling shops. This is a regulated industry and is considered in this analysis as part of the formal collection process.

Informal collection through waste pickers likely still contributes to the recycling of waste. In the South East Asia region, waste pickers are the key drivers of informal waste collection in urban areas. Their role in Thailand is not well-understood, and there is currently not much insight into this sector. Despite this significant role in the region, little is known about the actual recovery factor for both residential (non-landfill) and landfill waste pickers and how it varies across countries and in Thailand. This study has not considered this informal flow of waste, it is assumed that all recyclable material at some point passes a recycling shop and is registered there.

Recommended action: Local SWM authorities, possibly assisted by universities, local nongovernmental organizations (NGOs) or other relevant organizations, should undertake field studies to assess the material recovery factor for residential waste pickers. This could be implemented across a range of 'typical' LAOs to increase the overall understanding of the role of waste pickers in reducing plastic waste.

Indicator 4 - Uncollected plastic waste and losses from collection (uncollected plastic waste that is disposed on land, water, burned, or buried)

The NSO survey on household practices used to calculate this indicator is only available at the provincial level. Accurate estimates of MPW require a more in-depth understanding of and information on household practices at (sub)district level.

Recommended action: While the NSO data source is good, this study was not able to extract trends from annual data sources. Also, the NSO data source only provides insight into which handling practices are used by households, but not the frequency thereof and does not provide insight into which practice is used most often. Including a specific SWM question in the NSO annual survey module—for example, one that targets the frequency of waste handling practices—would be an important step in improving household practice data accuracy and relevance.

An additional action, particularly relevant for districts contributing significantly to uncollected plastic waste, would be to further specify and map the location of legal dumpsites, with the aim of providing more detailed information on waste accumulation and leakages in these areas.

Indicator 5 - Total recycled plastic waste (recovery from recycling shops and through informal collection)

As indicated, recycling in Thailand is a well-regulated formal industry. This study has not further looked into the flow of waste that enters recycling shops. It was assumed that waste that arrives at a recycling shop is either properly recycled and otherwise it is brought to a formal disposal facility. Little is known on the actual recycling rate and which types of (plastic) waste are recycled.

Recommended action: While in Thailand the amount of waste that arrives at recycling shops are registered, there were no data on the actual recycling rate. These facilities likely have good insight in the composition of (plastic) waste. Therefore, recycling shops should be required to provide a detailed overview of the amounts of the various types of waste that arrive at the locations and their individual recycling rate. They should also be required to provide insight into the amount of (plastic) waste rejected and where this is being disposed.

Indicator 6 - Total plastic waste disposed to formal disposal sites (disposal to formal disposal facilities [sanitary facilities and unsanitary facilities] + recycled plastic waste)

This study was provided with a detailed overview of the reported total amounts of solid waste that arrives at the various formal disposal facilities in the studied area. While it is generally acknowledged that this is very relevant and that these data are likely very reliable, more data could be gathered at the disposal facilities to be able to construct a better picture of the flow of (plastic) waste in Thailand.

Recommended action: At the facilities a daily log should be kept of how much solid waste arrives at the facility and where each truck comes from. Regular samples should be taken from truckloads to determine the composition of the solid waste. Ideally these samples are from different (sub)districts/LAOs to allow the construction of a more detailed waste flow analysis.

Indicator 7 - Mismanaged plastic waste ([uncollected plastic waste + losses from collection] + collected plastic waste disposed of in formal open dumpsites + fractions of plastic waste leaked from other formal disposal sites).

In general, information on mismanaged (plastic) waste is hard to obtain. While it is generally known where the unsanitary disposal facilities are, several discrepancies were found between the information provided by the LAOs and the databases from PCD. These discrepancies should be addressed and there should be a uniform classification system of the various formal disposal facilities.

Also, a problem that is not unique to Thailand, very little is known about how much (plastic) waste is uncollected and how much leaks from (un)sanitary disposal facilities. More research is required to gain insight into especially the latter one.

Recommended action: The area around controlled dumps and open dumpsites should be monitored to detect leakage of (plastic) waste. In the short term, cameras could be installed at the high-priority disposal facilities to capture leakage from these facilities. These images could be analyzed using new Artificial Intelligence (AI) methodologies to extract patterns and determine general trends that can be used to provide the scientific basis for the leakage and availability rates.

Indicator 8 - Mismanaged plastic available for wash-off (from sanitary facilities, controlled dumps, open dumping and fractions of mismanaged plastic waste).

Little is known about how much mismanaged plastic is available for and can wash off from the terrestrial environment. This is also not a problem unique to Thailand.

Recommended action: To obtain more insight in how much (plastic) waste is present in the environment at any one moment and how much washes off, in the short term, cameras could be installed at strategic locations (for example, near markets, known communal disposal locations, open dumpsites, and so on) in the critical districts to capture the amount of waste that accumulates at these locations and if and when it is mobilized. These images and data could then be analyzed to extract patterns and determine general trends that can be used to provide the scientific basis to further improve the models and underlying assumptions.

RECOMMENDATIONS FOR IMPROVING HYDROLOGICAL MODELING

In this section, specific recommendations are provided to improve the hydrological models.

Representativeness at small islands

The hydrological models of the small islands are considered very uncertain. These models have been set up based on remote-sensed data only and could not be calibrated/validated. There is lack of a long time series of observational data of discharges and runoff on the small islands. This is necessary to calibrate and validate the hydrological models for these areas.

Recommended action: Start collecting hydrological data at the small islands and in the small catchments. Discharges of the small rivers and runoff from storm-water systems on the islands can be monitored and the data collected.

Representativeness in highly irrigated areas

The hydrological models of the rivers running through highly irrigated areas (mostly the Mae Klong and Phetchaburi catchments) underperform. Due to the absence of datasets that describe the amount of water taken out from the rivers and used in the irrigation systems, the models for these areas could not be sufficiently calibrated/validated.

Recommended action: Register and collect datasets that describe the water taken out of the rivers and provide detailed datasets of water levels in and management schemes of reservoirs.

Representativeness at urban level

The hydrological models are generally coarse (1 km2) and only indirectly account for water management infrastructures. Although the models are generally representative at catchment level (as shown in Chapter 3), the model results are too coarse to specify detailed measures in highly urbanized areas such as Bangkok. However, further improving the representativeness of hydrological models in urban areas is not easy. To realistically account for urban storm-water infrastructure, reservoirs, polders, and so on, a detailed hydraulic model is required. Because realistic runoff modeling is an essential part of the approach to be able to quantify wash-off of exposed MPW, such a model needs to have a rainfall-runoff component. Setting up a hydraulic model with these capabilities requires thorough validation and calibration and therefore a significant amount of observation data. At the same time, it also requires more detailed and reliable data on exposed MPW, data that are currently not available, especially for Bangkok (see previous section).

Recommended action: It is recommended to first improve the SWM data and SWM model before considering improving the hydrological models for urban areas. Once better SWM data and an improved SWM model is available, it is recommended to evaluate if improving the hydrological models to the described level of detail is required and will provide the necessary additional information to inform policy.

RECOMMENDATIONS FOR IMPROVING MODELING OF PLASTIC WASTE DISCHARGES

Modeling of fate and transport of plastics in rivers is still in its infancy and presents a great number of challenges. Apart from relying on SWM and exposed MPW input data, plastic waste discharge modeling limitations are primarily related to model parameters of wash-off, transport and fate, and the validation of the model results with field measurements.

While the latter is related to lack of observation data that could be used to validate the model outputs, the first corresponds to a current knowledge gap in the scientific domain, for which several assumptions needed to be made.

Knowledge of plastic behavior and fate in rivers

Processes of weathering/fragmentation, interaction with the sediment and vegetation in rivers is scientifically poorly described and documented. It is expected that these will depend on the particular features of each catchment, as well as the characteristics of the predominant plastic waste (that is, polymer/density, shape, size).

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 (for example, 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. The following data are recommended to improve the models in their present configuration:

- Quantification of the relation between runoff rate and mobilization of plastic on various surfaces (paved and unpaved)
- Investigation and quantification of trapping behaviors on land (for example, trapping of plastics by vegetation and/or anthropogenic structures)
- Investigation and quantification of fragmentation rate of plastics by polymer type and size, exposure to weathering processes (for example, traffic, UV radiation)
- Investigation and quantification of settling rates of plastic in the water column as a function of size, polymer type
- Investigation and quantification of trapping of plastics in riverine vegetation
- Effectivity of trash racks and waste barriers including management practices
- Incorporation of trash racks and waste barriers into the model

Observation data to improve calibration and validate model results

There is lack of a long time series of observational data of plastic waste amounts being transported and discharged by rivers. This is necessary to build evidence on the high spatial and temporal variability and to help define the factors that affect it, which will be a combination of anthropogenic (for example, waste handling practices) and environmental conditions (rainfall, typology of catchments, and so on). Actual measurement data will help to validate model results and improve modeling simulations, aligning the simulated estimations that result from using SWM data (upstream processes), with real measurements of plastic fluxes and discharges (downstream results).

It is important to highlight that to build a solid picture of such complex and dynamic issue, it is necessary to collect and integrate different data sources, using different analytical and modeling tools, as well as covering the different environmental domains where plastic waste flows through and accumulates.

Recommended action: Readily available opportunities may exist to couple continuous and ongoing clean-up operations in certain rivers (e.g., trash racks, clean-up initiatives being developed at the river mouth) with monitoring the amounts and composition of plastic waste intercepted in the river.

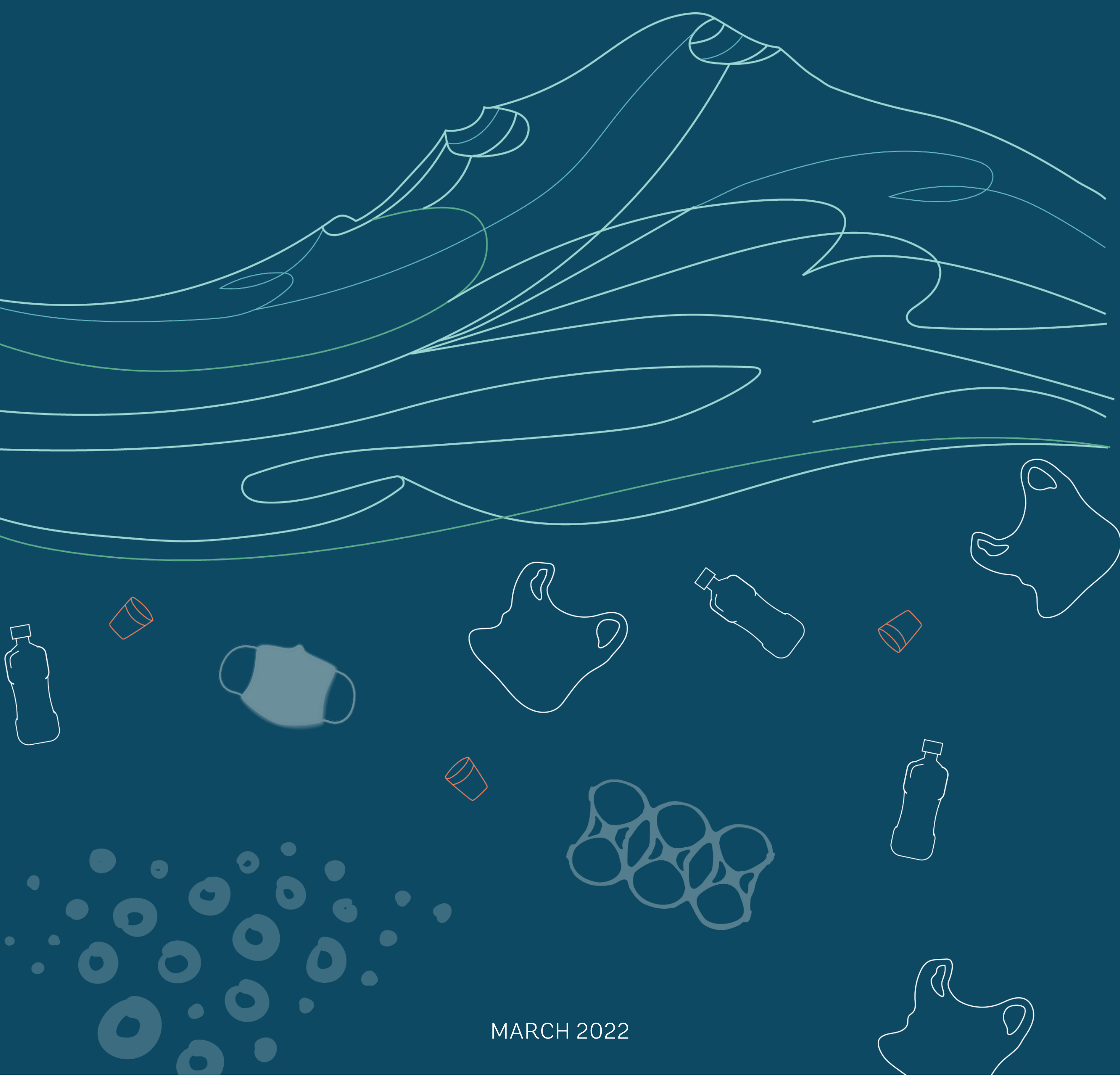
Specifically, regular samplings of waste removed should be analyzed in terms of:

- Volume, dry and wet mass of plastic waste, in view of establishing a robust index of plastic content that can be used to extrapolate for larger volumes of plastic waste removed in a certain area.
- Analysis of the composition of plastic waste, following a detailed categorization of items, using a harmonized-items list for Thailand, and ideally within the region, to enable comparison with other environmental compartments (for example, plastic debris surveys on beaches), as well as with waste streams data and discharges estimates.

The frequency of sampling will depend on the purpose of the sampling:

- Higher frequency of sampling in a short period of time, in different seasons and covering different years, to assess the influence of the daily, seasonal, and yearly hydrological variability and help calibrate discharge models.
- Lower frequency but more detailed sampling for continuous periods throughout the year(s), to monitor the impact of preventive measures on the volume of leaked waste, as well as the impact of policies that target specific plastic waste items (for example, plastic bags).

Interestingly, the detection of plastic pollution using remote sensing technologies (drones, satellites) is an emerging field of research (for example, Biermann et al. 2020; Martínez-Vicente et al. 2019) that has the potential to generate high frequency/broad coverage data on plastic waste in rivers and coastal waters (possibly even accumulated), that would be very valuable.



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