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Determination of Plastic Leakage and Fates from Solid Waste Management Chain: Thaklong Municipality, Pathumthani Province, Thailand

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Abstract

Plastic waste enters the environment mostly through mismanagement practices like as open burning, illegal dumping, and waterway disposal. Inefficient solid waste management practices worsen the situation of plastic waste leaking the natural environment. The study of the situation of municipal solid waste management (MSWM) and plastic leakage from MSWM system is critical for preventing plastic pollution in the environment. This study assessed MSWM system using the Waste Wise Cities Tool method and estimated the amount of plastic leakage from MSWM system using Waste Flow Diagram method in Thaklong, Klong Laung district, Pathum Thani province, Thailand. In Thaklong, it is estimated that waste generation was 130 tons/day and organic waste was 64 % as the biggest percentage of the total waste and plastic waste about 18 % as the second-biggest component. There was 926 tons of plastic pollution annually, of this, 90.67% came from uncollected waste, 9.04% from collection services, and a tiny amount came from other sources like sorting and transportation. These results indicated that plastics could leak from the MSWM system itself. Plastic leakage from MSWM system and fates of plastic leakage especially land, drains, water systems, and plastic waste openly burnt can be visualized as the largest amount of plastic waste (511 tons/year) retained on land and 284 tons/year of plastic leaks into the water systems as the second largest, while some were openly burned at 120 tons/year and accumulated in drains at 11 tons/year. The present study is one of the projects to assist the policymakers, especially local government, and environmental managers in developing the improvement of MSWM system and more effective measures to solve plastic pollution challenges.

Keywords: Fates of plastic leakage, Municipal solid waste management system, Plastic leakage, Plastic Pollution, Plastic waste, Solid waste management practices

စွန့်ပစ်ပစ္စည်း စီမံခန့်ခွဲမှု ကွင်းဆက်မှ ပလပ်စတစ် ယိုစိမ့်မှုနှင့် ပတ်ဝန်းကျင်သို့ ရောက်ရှိမှု အခြေအနေကို ဆန်းစစ်ခြင်း

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ပလတ်စတစ်စွန့်ပစ်ပစ္စည်း အများစုသည် လွဲမှားသောစီမံခန့်ခွဲမှုများဖြစ်သည့် လေဟာပြင် အမှိုက်မီးရှို့ခြင်း၊ စည်းကမ်းမဲ့ ကုန်းမြေတွင် အမှိုက်ပစ်ခြင်းနှင့် ရေလမ်းကြောင်းများတွင် အမှိုက်ပစ်ခြင်းတို့မှတဆင့် ပတ်ဝန်းကျင်သို့ ရောက်ရှိလျက်ရှိပါသည်။ စွန့်ပစ်ပစ္စည်း စီမံခန့်ခွဲမှု မလုံလောက်ခြင်းကြောင့် သဘာဝပတ်ဝန်းကျင်သို့ ပလတ်စတစ်စွန့်ပစ်ပစ္စည်းများ ယိုစိမ့်မှုကို ပိုမိုဆိုးရွားစေလျက်ရှိပါသည်။ စွန့်ပစ်ပစ္စည်း စီမံခန့်ခွဲမှု အခြေအနေနှင့် စွန့်ပစ်ပစ္စည်းစီမံခန့်ခွဲမှုစနစ်မှ ပလတ်စတစ်စွန့်ပစ်ပစ္စည်းများ ယိုစိမ့်မှုအခြေအနေအား လေ့လာခြင်းသည် ပလတ်စတစ်ညစ်ညမ်းမှုကို တားဆီးကာကွယ်နိုင်ရေးအတွက် အရေးပါလှပါသည်။ ယခုသုတေသနစာတမ်းသည် ထိုင်းနိုင်ငံ၊ Pathum Thani ပြည်နယ်၊ Klong Laung ခရိုင်၊ Thaklong မြို့၏ စွန့်ပစ်ပစ္စည်း စီမံခန့်ခွဲမှု အခြေအနေကို Waste Wise Cities Tool နည်းလမ်းကို အသုံးပြု၍ လည်းကောင်း စွန့်ပစ်ပစ္စည်းစီမံခန့်ခွဲမှုစနစ်မှ ပလတ်စတစ်စွန့်ပစ်ပစ္စည်းများ ယိုစိမ့်မှုအခြေအနေအား Waste Flow Diagram ကိုအသုံးပြု၍ လည်းကောင်း ဆန်းစစ်ဖော်ထုတ်ထားသည့် စစ်တမ်းဖြစ်ပါသည်။ Thaklong မြို့၏ စွန့်ပစ်ပစ္စည်းထွက်ရှိမှုမှာ စုစုပေါင်း တစ်နေ့လျှင် တန်ချိန် ၁၃၀ ခန့် ထွက်ရှိကြောင်း၊ သြဂဲနစ်စွန့်ပစ်ပစ္စည်းသည် အများဆုံးဖြစ်ပြီး ပမာဏမှာ စုစုပေါင်း စွန့်ပစ်ပစ္စည်းပမာဏ၏ ၆၄ ရာခိုင်နှုန်း ရှိကြောင်း၊ ဒုတိယအများဆုံးမှာ ပလတ်စတစ် စွန့်ပစ်ပစ္စည်းများဖြစ်ပြီး ပမာဏမှာ ၁၈ ရာခိုင်နှုန်း ခန့်ရှိကြောင်း ခန့်မှန်းသိရှိရပါသည်။ ပလတ်စတစ်ညစ်ညမ်းမှုပမာဏမှာ နှစ်စဉ် ၉၂၆ တန်ခန့် ဖြစ်နေကြောင်း၊ မသိမ်းဆည်း နိုင်သော စွန့်ပစ်ပစ္စည်းများမှ ၉၀.၆၇ ရာခိုင်နှုန်းခန့်၊ အမှိုက်သိမ်းဆည်းသည့် ဝန်ဆောင်မှု များမှ ၉.၀၄ ရာခိုင်နှုန်းခန့်နှင့် အမှိုက်အမျိုးအစား ခွဲခြားခြင်းနှင့် သယ်ယူပို့ဆောင်ခြင်း စသည့်လုပ်ငန်းများမှ ပမာဏအနည်းငယ်ခန့် ယိုစိမ့်ထွက်လာခြင်းဖြစ်ကြောင်း လေ့လာ တွေ့ရှိရပါသည်။ ရလဒ်များအရ စွန့်ပစ်ပစ္စည်း စီမံခန့်ခွဲမှုစနစ်အတွင်းမှ ပလတ်စတစ် စွန့်ပစ်ပစ္စည်းများ ယိုစိမ့်လာနိုင်ကြောင်း ဆန်းစစ်တွေ့ရှိရပါသည်။ စွန့်ပစ်ပစ္စည်းစီမံခန့်ခွဲမှု စနစ်မှ ပလတ်စတစ်စွန့်ပစ်ပစ္စည်းများ ယိုစိမ့်မှုနှင့် ပတ်ဝန်းကျင်သို့

ရောက်ရှိနေသည့် ပမာဏအား ဆန်းစစ်ရာ နှစ်စဉ် ပလတ်စတစ်စွန့်ပစ်ပစ္စည်း ၅၁၁ တန်ခန့်သည် မြေပြင် ပေါ်တွင် အများဆုံး ရောက်ရှိ နေကြောင်း၊ ၂၈၄ တန်ခန့်သည် ရေမြောင်းစနစ်အတွင်းသို့ ဝင်ရောက်သွားကြောင်း၊ ၁၂၀ တန်ခန့်မှာ လေဟာပြင် မီးရှို့ခံရကြောင်းနှင့် ရေမြောင်းများတွင် ၁၁ တန်ခန့် စုပုံနေကြောင်း ခန့်မှန်းသိရှိ ခဲ့ရပါသည်။ ယခုစာတမ်းသည် စွန့်ပစ်ပစ္စည်း စီမံခန့်ခွဲမှုစနစ် တိုးတက် ကောင်းမွန်ရေးနှင့် ပလတ်စတစ် ညစ်ညမ်းမှုဆိုင်ရာစိန်ခေါ်မှုများကို ဖြေရှင်းရန် ပိုမို ထိရောက်သော အစီအမံများ ရေးဆွဲ အကောင်အထည်ဖော်ရာတွင် မူဝါဒချမှတ်သူများ၊ ဒေသဆိုင်ရာ အစိုးရနှင့် ပတ်ဝန်းကျင်ဆိုင်ရာ စီမံခန့်ခွဲသူများအား အထောက်အကူပြုသည့် စာတမ်းတစ်ခု ဖြစ်ပါကြောင်း တင်ပြအပ်ပါသည်။

Determination of Plastic Leakage and Fates from Solid Waste Management Chain: Thaklong Municipality, Pathumthani Province, Thailand

1. Introduction

At present, Municipal Solid Waste (MSW) has become a major concern, as the amount of waste generation has increased tremendously due to rapid urbanization and industrialization, population growth, and improved lifestyles (UNEP, 2017). The world generates 2.01 billion tons of MSW annually (Silpa et al., 2018). About 50 % of global waste generation is an organic waste on average, followed by plastic is about 12 %. About 37 % of global waste is disposed of in the landfill, open dumping accounts for about 33 % of waste, 19 % is recovered and 11 % is incinerated. World Bank estimated that global waste will grow to 3.40 billion tons by 2050. Currently, the adequate collection and disposal of MSW is a global challenge, particularly impacting developing countries. According to current estimates, 2 billion people worldwide have no access to waste collection services, and 3 billion people's waste is managed in an environmentally unsound manner (Wilson et al., 2015). This has severe impacts both on human health and the environment, with one rapidly emerging problem being plastic pollution.

Plastic pollution is one of the most pressing environmental issues, too as the rapidly increasing production of disposable plastic products. It is most visible in developing Asian and African countries, where waste collection systems are often inefficient or solid waste management system is ineffective (Parker, 2019). Over 300 million tons of plastic are produced every year globally (IUCN, 2018). Global plastic production has been more than 6,300 million tons since the 1950s, of which 360 million tons of plastic were produced in 2018 alone. Almost half of the global plastic production is responsible for packaging (Geyer et al., 2017). Most plastics from this production finally become plastic waste as plastic is discarded as waste after using them. It is estimated that only 9 percent of the total global plastic waste is recycled, and 12 percent is burned or incinerated currently, the remaining 79 percent is disposed on landfills or leaks into the natural environment (Cottom et al., 2020).

Plastic waste in the natural environment gradually breaks down into smaller plastic debris through various degradation processes (Andrady, 2011). Plastic debris can be mainly classified into macroplastics with higher than 5 mm in diameter (Driedger et al., 2015) and microplastics with less than 5 mm in diameter (Cole et al., 2011). Microplastics can be classified as primary microplastics that are plastics with a microscopic size intentionally produced as plastic resin pellets or as additives for personal care products and secondary microplastics come from the degradation of larger plastic debris (Peter et al., 2009). The plastic leakage starts from land to water systems and ends up in the ocean. Once plastic wastes reach the oceans, the larger plastic items degrade into innumerable secondary microplastics and have deadly impacts on marine life and the health of the oceans. It is therefore paramount to prevent macroplastic pollution at the source before it becomes uncontrolled in the environment, and potentially enters water bodies or water systems.

According to (IUCN, 2018), at least 8 million tons of plastic end up in our oceans every year. About 20 % of plastic leakage into the ocean originates from ocean-based sources and so about 80 % of ocean plastic comes from land-based sources. Of the plastic leakage from land-based sources, 75 percent comes from uncollected waste, while the remaining 25 percent leaks from within the waste management system itself (Ocean Conservancy, 2015).

In recent years, plastic leakage and the fates of plastic leakage from solid waste management practices and plastic pollution in the environment have been studied and reported in some developed countries. However, there is still a small number of studies in the developing SEA region (PCD, 2019). Thailand is one of the world's biggest contributors to ocean waste and one of the major plastic producers in Asia (Khanunthong, 2021). Population growth with economic development has caused an increase in plastic usage, increasing plastic waste generation. About 80% of all plastic waste generated in Thailand consists of single-use plastic bags (PCD, 2019). Much of this plastic ends up in the environment, notably marine ecosystems; approximately 65.3% of waste collected from Thailand's natural environments in 2018 was plastic packaging waste (PCD, 2019). It was shown that the inefficient collection and improper disposal of municipal solid waste exacerbate the situation of plastic waste ends up in the marine environment (Akenji et al., 2019; PCD, 2019). All these facts indicate that learning more about how much plastic waste leaked from the solid waste management chain and the fates of plastic leakage, especially on land, drains, water systems, and openly burnt, is critical and essential to identify the high-priority sources of plastic pollution to make informed interventions for reducing plastic leakage from the municipality solid waste management (MSWM) system and plastic pollution in the environment. This study assessed MSWM system using the Waste Wise Cities Tool method and estimated the amount of plastic leakage from MSWM system using Waste Flow Diagram method in Thaklong, Klong Laung district, Pathum Thani province, Thailand.

2. Objectives

The overall objective of this study is to determine the leakage and fates of plastic from the solid waste management chain in Thaklong Town, Thailand.

(a) To determine MSW generation, composition, and waste flow within the MSWM system in Thaklong using the WaCT method,
(b) To estimate plastic leakage and fates from the MSWM system and plastic pollution per fate in Thaklong using the WFD method.

3. Materials and Methods

3.1 The Overview of Methodology Framework

This study needed both primary and secondary data. The secondary data was collected especially for MSWM data and business license data from the municipal office. The primary data collection was mainly focused on this study. MSWM data collection and analysis were conducted based on the methodology of Waste Wise Cities Tool (WaCT). Waste Flow Diagram (WFD) method was mainly applied for plastic leakage and fate from MSWM system assessment.

Household waste sampling and composition analysis, non-household waste generation interview-based survey, MSW received by sorting or recovery facilities and MSW disposed site visit and interview, composition analysis of MSW disposed were conducted based on WaCT methodology. The MSWM data collected by WaCT method was used to calculate overall MSW composition according to WFD method, which is important to assess plastic leakage and fate from the MSWM system. Other required MSWM data was collected from Thaklong municipal office and website such as population and community data, MSW collected or disposed daily data and business license data for non-household types and recycle firms etc. For determination of plastic leakage and fate potential levels from the MSWM system, field observation was carried out the surroundings along MSWM practices that may lead to plastic leakage into the environment within the study area. The duration of data collection and analytical work for the research study is from October 2021 until April 2022. The framework of methodology is shown in **Figure 1.**

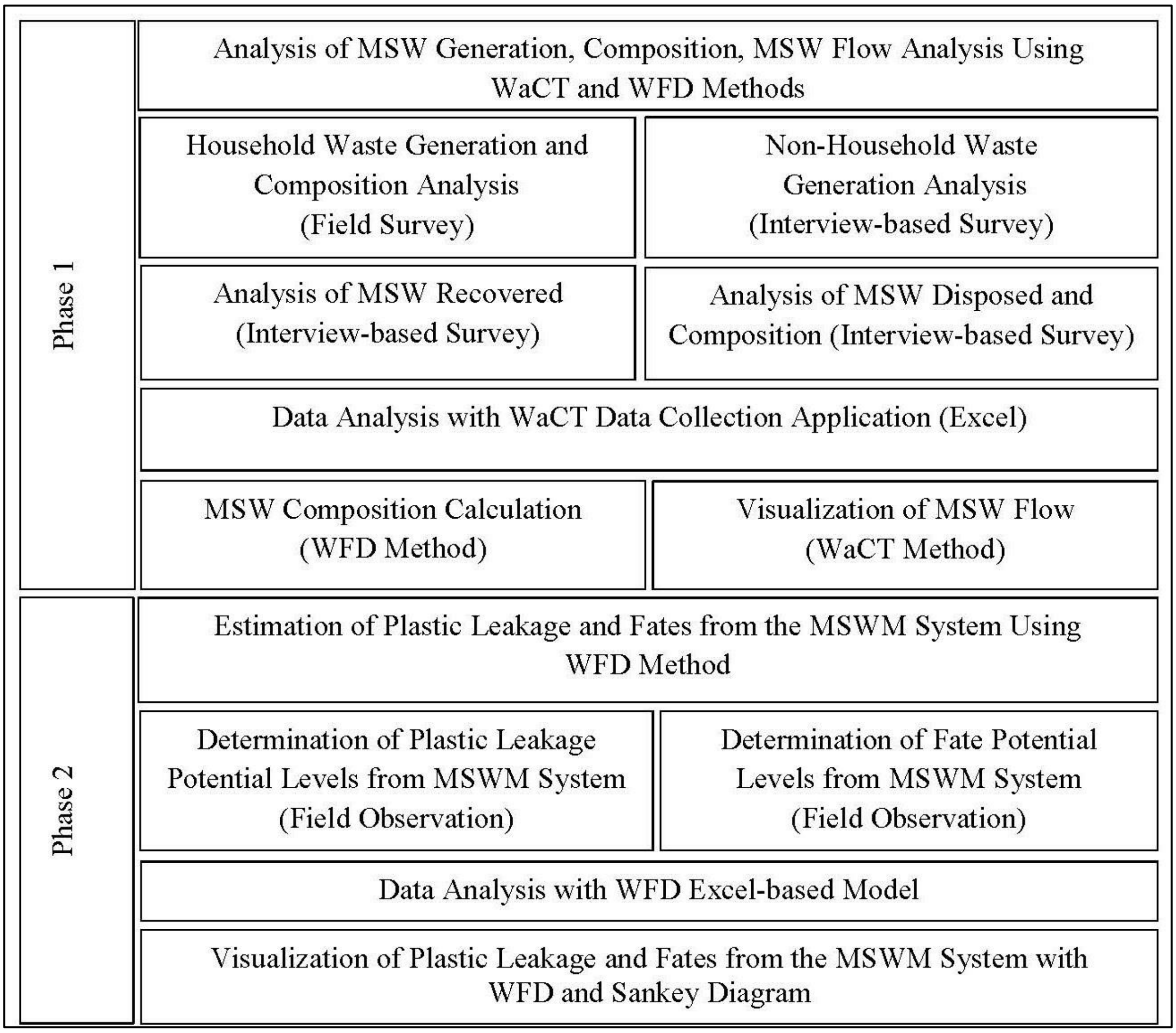


Figure 1: Framework of methodology

3.2 Study area

Thaklong Municipality was selected as the study area, located in Khlong Luang District, Pathum Thani Province, Thailand, with an area of 63 square kilometers, covering Khlong Song Sub-district and some areas of Khlong Naung Sub-district. It has 43 communities including Khlong Naung Sub-district and Khlong Song Sub-District, as shown in **Figure 2.** According to information of Thaklong Municipal website, population and household statistics as of 26th January 2021, population is 77104 and household number is 56353. Seasons are rainy season from mid-May to mid-October, winter from mid-October to mid-February, and summer from mid-February to mid-May.

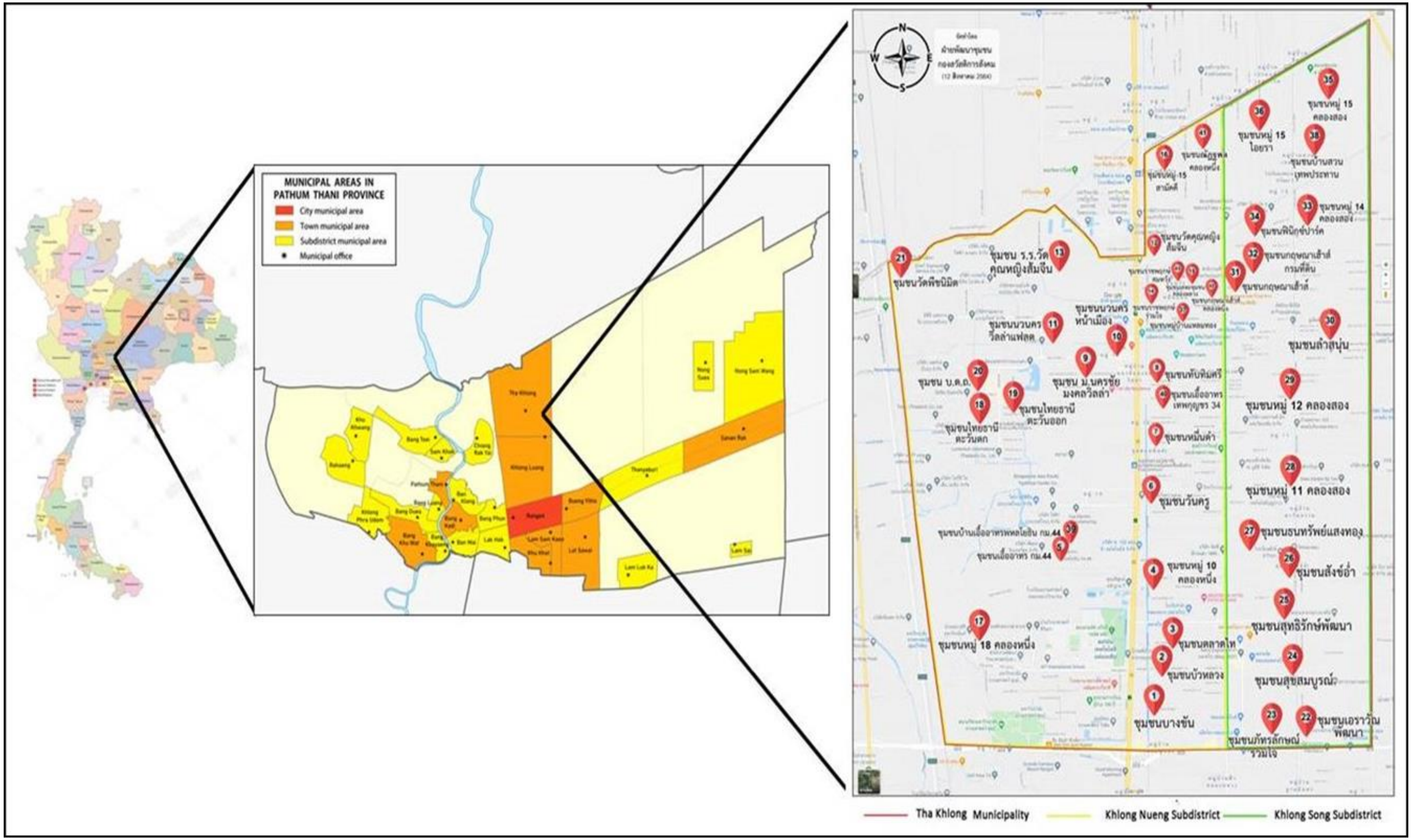


Figure 2: Study area: Tha Khlong

3.3 Analysis of MSW Generation, Composition Using WaCT and WFD Methods

Data collection and analysis of MSW generation includes household waste sampling and composition analysis and non-household waste generation interview-based survey based on WaCT method. In investigation of waste flow in terms of MSW generated, collected (i.e. recovered and disposed) and uncollected within the MSWM system, not only MSW generation analysis but also assessment of MSW received by sorting or recovery facilities and MSW disposed, composition of MSW disposed were conducted based on WaCT methodology. Overall MSW composition required for the WFD method was calculated according to WFD methodology.

3.3.1 Household Waste Generation and Composition Analysis with WaCT Method

For household waste sampling and composition analysis, sample size 41 was properly defined due to the resource limitations such as labors, time and money, limitation of household participation and some restrictions regarding Covid-19 pandemic, whereas sample size is 41 if confident level is 80 % and precision level is 10 % defined by Cochran's formula as follows, for the random sampling method.

$$n = \frac{n_0}{1 + \frac{(n_0 - 1)}{N}}$$

Where,

$$n_0 = \frac{z^2 pq}{e^2}$$

n = Sample size,
N = Population size
z = Selected critical value of desired confidence level (z value is used from standard statistics table),
p = Estimated proportion of an attribute that is present in the population (Assuming the maximum variability in a population is 50%, p = 0.5),
q = Estimated proportion of an attribute that is not present in the population (q = 1 – p)
e = Desired level of precision

Due to sampling size is 41, assuming 45, 15 households for each high-, middle- and low-income level were collected their household wastes as sample solid waste for household waste generation and composition analysis. Income level was defined according to three different housing types by following the Waste Wise Cities Tool methodology, as shown in **Table 1** and **Figure 3.**

The collected waste bags were distributed to the selected households and the number of residents was recorded before the sampling day one. Firstly, the collected waste bags from each household for each day separately was weighed and recorded the weight. An empty bag was weighed and but not significant so was neglected the bag weight. After weighing the individual sample per household per day have been recorded, the waste in the bags was spread on the plastic sheet. The samples were mixed, as the composition was wanted to analyze an average for the whole sample (i.e., not per household per day). The waste was categorized into the six sorting categories (paper, plastic, glass, metal, organic and other) and then each fraction was weighed and recorded, shown in **Figure 4.** Household waste generation and composition analysis was done as the same procedure for seven days.

Population of the town, the recorded waste data, number of residents in each household was entered into the WaCT excel-based model, called WaCT data collection application (DCA), then calculate household waste generation and composition, household waste generation per capita per day.

Table 1: Income Level and Housing Types

Income level	**Housing Type Example**
High	Luxury condominium, single detached house with garden, sophisticated alarm systems.
Middle	Apartments, single detached house without garden.
Low/ informal settlements	Slums, apartments with single rooms, apartments mud house, Rent less than 5% of GDP per capita

Figure 3: Different Income Level Housing Types (A) High, (B) Medium, (C) Low

(A)

(B)

Figure 4: Household Waste Sampling Survey (A) Collection Stage (B) Weighing and Sorting Six Waste Categories Stage

3.3.2 Non-household Waste Generation Analysis

For non-household waste generation, interview-based survey was done in various premises and institutions such as hotels, universities, offices, hospitals, markets, and public space etc. selected according to the WaCT's recommended different units for different non-household sources as the WaCT's recommended units for aggregation of generations rates in premises and institutions described in **Table 2.** At least 2 or 3 number of premises and institutions for each different non-household type were interviewed. The non-household premises and institutions generating MSW or their contracted collection companies were interviewed about their average waste generation daily**.** When interviewing premises and institutions, if it was possible, the waste was weighed. In case of public space, the responsible waste collection trucks were interviewed to obtain average waste collected tonnage of waste daily from the public space.

To calculate per unit waste generation from different premises and institutions, once the data from all the premise types and public spaces was collected, data was entered into the WaCT data collection application (DCA). The total number of units (rooms, tables/chairs, students, employees, stalls, beds, square meters etc.) derived from the business licensing data and public space data was entered into the WaCT DCA to calculate total waste generation per day from each premise and total waste generated from non-household sources. After finishing the data entry for both household and non-household, WaCT DCA resulted total MSW generation and MSW generation per capita per day.

Table 2: Units for Aggregation of Generation Rates in Premises and Institutions

Premises/Institutions	**Recommended Unit**
Hotel	number of beds
Restaurant	number of tables/chairs
Schools	number of pupils
Offices	number of employees; Square meters

Markets	number of stalls; type of goods (vegetable market, electronics market)
Hospitals	number of beds
Public spaces	square meters

3.3.3 Analysis of MSW Recovered by Recycling or Sorting Facilities

MSW recovered was analyzed by interviewing the recycling or sorting facilities with the questionnaires designed based on the required information. The recycling or sorting facilities was interviewed and the obtained information from the recycling or sorting facilities was entered into the WaCT DCA for calculation of MSW recovered amount and total collected MSW.

3.3.4 Municipal Solid Waste Disposed and Composition Analysis

3.3.4.1 MSW Disposed. The data of average MSW disposed amount daily was collected by interviewing the responsible persons from municipal office and disposal facility owner. The responsible person of disposal facility was interviewed not only the average MSW disposed amount daily but also the average daily estimated amounts per material diverted from disposal for recovery such as energy recovery and whether there are sorting activities in the disposal facility by the waste picker or the facility's workers and then interviewed the average daily estimated amount of waste sorted in the disposal site. The obtained information from the municipal office and disposal facility was entered into the WaCT DCA for actual MSW disposal amount and total collected MSW calculation.

3.3.4.2 Composition Analysis of MSW Disposed. The composition analysis of MSW disposed was conducted from three trucks. For this analysis, the flat ground surface with enough space was selected and then the surface was covered with a thick plastic carpet to deposit waste samples. The waste samples were analyzed by the quartering method as shown in **Figure 5.** This method was used to reduce the sample size of wastes. First, waste was mixed as thoroughly as possible on the plastic carpet and then piled into a cone shape. Then, they were divided into four parts (A, B, C, D) and from those four parts, discard two opposing quarters (A+C) and then mix the remaining two quarters (B+D). If there is high volume of solid waste, then continued same procedure until approximately one quarter of the size of the original sample. The waste samples were sorted into the six categories (paper, plastics, glass, metals, organics and other) and finally weigh the waste fractions and recording the weight, shown in **Figure 6**.

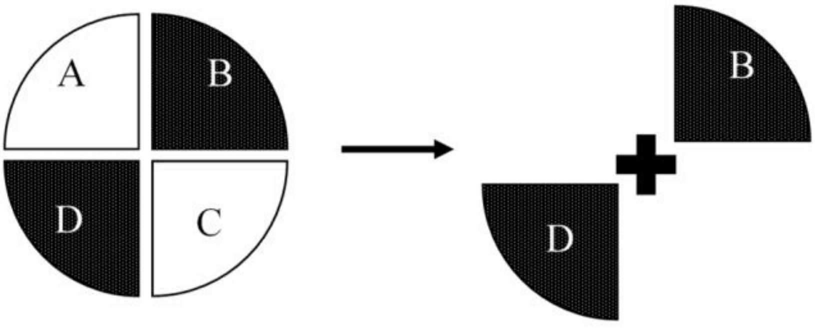


Figure 5. Quartering method

Waste composition percentage was calculated by using the following equation.

$$\text{Waste Composition (\%)} = \frac{W_1 \times 100}{W_2}$$

Where, W_1: The weight of components of solid waste (kg)
W_2: The total weight of solid waste (kg)

(A)

(B)

Figure 6: MSW Disposed and Composition Analysis (A) Waste Placement and Quartering Method (B) Sorting six waste categories and Weighing Each Waste

3.3.5 MSW Composition Calculation by WFD Method

Overall MSW composition is the required information for the investigation of plastic leakage and its fates from the solid waste management chain. Data requirements and method to calculate MSW composition shown in **Table 3**. In this calculation, waste fractions for MSW uncollected were assumed same as the composition of a household waste composition according to the guidelines of the WFD methodology. Other required data are got from the survey and interview based on the WaCT method.

Table 3: Data requirements and method to calculate MSW composition from MSWM data collected by WaCT

Description	Paper/ Cardboard	Plastics	Glass	Metal	Other	Organic	Total
MSW recovered	PC_R	P_R	G_R	M_R	Ot_R	O_R	T_R
MSW disposed (mass/day)	PC_D	P_D	G_D	M_D	Ot_D	O_D	T_D
MSW Uncollected (mass/day)	PC_U	P_U	G_U	M_U	Ot_U	O_U	T_U
Extracted from disposal sites (If available)	PC_{ED}	P_{ED}	G_{ED}	M_{ED}	Ot_{ED}	O_{ED}	T_{ED}
Total MSW	$PC_T = PC_0 + PC_R + PC_U - PC_{ED}$	$P_T = P_0 + P_R + P_U - P_{ED}$	$G_T = G_D + G_R + G_U - G_{ED}$	$M_T = M_D + M_R + M_U - M_{ED}$	$Ot_T = Ot_D + Ot_R + Ot_U - Ot_{ED}$	$O_T = O_D + O_R + O_U - O_{ED}$	$T_T = T_D + T_R + T_U - T_{ED}$
MSW Composition	$(PC_T/T_T).100$	$(P_T/T_T).100$	$(G_T/T_T).100$	$(M_T/T_T).100$	$(Ot_T/T_T).100$	$(O_T/T_T).100$	100%

3.4 Estimation of Plastic Leakage and Fates from the MSWM System Using WFD Method

For estimation of plastic leakage and fate potential levels from the MSWM system, it is necessary to determine plastic leakage potential levels of leakage influencers and fate potential levels of different leakage types from the MSWM system by observation-based assessment. Field observation was carried out the surroundings along MSWM practices that may lead to plastic leakage into the environment within the study area. After determining these plastic leakage potential levels and fate potential levels, the determined leakage and fate potential levels and the obtained MSWM data were entered into the WFD excel model for data analysis. The results were visualized by the WFD system map and Sankey Diagram.

3.4.1 Determination of Plastic Leakage and Fate Potential Levels from MSWM System

Field observation was carried out to do observation-based assessment for determination of plastic leakage and fates potential levels from the MSWM system to estimate how much of the leaked plastic ends up in each fate. In this study area the two main canal water systems Khlong Naung and Khlong Song canals are connected to Chao Phraya River through Klong Rangsit canal, which flows finally into the Gulf of Thailand. Most of communities are settling near Khlong Naung and Khlong Song canals. Some business centers, fresh markets and institutions are also placed near these canals. Therefore, these canals have a high chance for plastic leakage and finally reach into the marine environment. Field observation was mainly conducted along Klong Naung and Klong Song canals in the study area and randomly in as many different locations as much as possible in the study area.

Throughout the field observation, photographs were taken to record the activities and the events related to SWM and the environmental issues surrounding SWM in the study area. They will contribute to observational based assessment for making assumptions to define plastic leakage potential levels per leakage influencer and plastic pollution levels per fate to determine plastic leakage and fates by using the corresponding descriptive tables described in the WFD User Manual.

Regarding plastic leakage from collection, transportation, field investigation was conducted based on the plan MSW collection, collection, and transportation routes of MSWM department obtained from the municipal office while plastic leakage from informal value-chain collection, formal sorting and informal service-chain sorting was inquired for field observation. Field investigation regarding disposal facilities was conducted at disposal facility with the owner's permission with MSW disposed interview.

Field observation regarding plastic leakage from the MSWM system was conducted based on the factors described in **Table 4.** Plastic leakage potential levels of different leakage influencers from MSWM System were determined according to the corresponding descriptive tables for the leakage potential levels of different leakage influences described in WFD user manual**.**

Table 4. Basic Factors for Field Observation regarding Plastic Leakage

Plastic Leakage Source	**Factors for Field Observation**
Collection Services	Frequency of collection, capacity of the bins, storage of bins, coverage of bins, collection service delay, loading method of collection vehicles, capacity of primary transportation vehicles and frequency of collected waste transfer
Informal Value-Chain Collection	Release of waste into the environment, practices such as overturning bins to get access to valuable material and discarding unwanted items during the collection, capacity of transportation vehicles
Formal Sorting and Informal Service-Chain Sorting	Dispose of sorting rejects in the formal collection system, dumping or open burning of rejects
Transportation to Disposal	Capacity of transportation vehicles, coverage of collection vehicles
Disposal Facilities	Dumpsite locations (flooding and landslides), exposure to weather (heavy and persistent winds or surface runoff), waste handling, waste pickers occurrence, waste pile above or below the ground, coverage of waste, burning of waste, fencing
Storm Drains to Water Systems	Frequency of rainfall and heavy storms events, climate, frequency of drain cleaning

In the WFD method, each leakage flow was assigned to one of four leakage types as follows.

1. Voluntary leakage means that waste was purposefully put in the environment. (e.g., dumped / burnt)
2. Involuntary leakage means that waste accidentally escaped into the environment. (e.g., wind-blown)
3. Diffuse leakage means that leakage occurs over a large, dispersed area. (e.g., collection containers)
4. Point source leakage means that leakage occurs from one of more set locations. (e.g., dumpsites)

The allocation of these leakage types is summarized for each individual leakage flow in **Table 5.**

Table 5: Allocation of leakage flows to fate

Leakage Flow	Diffuse Voluntary	Diffuse Involuntary	Point Source Voluntary	Point Source Involuntary
Uncollected waste	■			
Plastic leakage collection services		■		
Plastic leakage from informal value-chain collection		■		
Plastic leakage from formal sorting			■	
Plastic leakage from informal service-chain sorting			■	
Plastic leakage during transportation to disposal		■		
Plastic leakage from disposal facilities				■

Regarding fates of plastic leakage, field investigation was mainly conducted along the two main canals in the study area and randomly in as many different locations as much as possible in the study area. The located area of formal and informal sorting facilities was inquired and visited during field observation.

Field observation regarding fates of plastic leakage from the MSWM system was conducted based on the factors described in **Table 6.** Fate leakage potential levels of different leakage types from MSWM System were determined according to the corresponding descriptive tables for the fate potential levels of different leakage types described in WFD user manual**.**

Table 6: Basic Factors for Field Observation regarding Fates of Plastic Leakage

Fates	Factors for Field Investigation
Burnt	- In areas without waste collection services, evidence of open burning - Evidence of sorting facilities openly burning their sorting rejects
Land	- In areas without waste collection services, evidence of dumping to land and street sweeping occurrence - In the study area and sorting facilities, evidence of quantities of plastic remaining on land (including that caught in vegetation) and street sweeping occurrence - Evidence of sorting facilities dumping their sorting rejects to land

Drain	- In areas without waste collection services, evidence of dumping to drains and frequency of drains cleaning - In the study area and sorting facilities, evidence of quantities of plastic entering drains and frequency of drains cleaning - Evidence of sorting facilities dumping sorting rejects to drains and cleaning of the drains within the vicinity that may be collecting any waste dumped to drains
Water systems	- In areas without waste collection services, occurrence of the residents in close proximity (< 500 m) to water systems - The study area and sorting facilities in close proximity (< 1 km) or not (>1 km) to water systems - Occurrence of vegetation on the banks of the water systems - Occurrence of sorting facilities in close proximity (< 500 m) to water systems

3.4.2 Data Analysis with WFD Excel-based Model

The WFD Excel-based Model was used for analysis of primary data from field surveys, interviewing, data regarding plastic leakage and fates from observation-based assessment and some secondary data. Data regarding MSW generation, waste treatment and disposal, plastic leakage potential levels per leakage influencer and plastic pollution levels per fate were all main necessary inputs for WFD excel-based model to calculate the amount of plastic leakage and fate. Then, it analyzed the data and then give the waste management result and unmanaged plastic including plastic leakage and fates of plastic leakage result summary tables.

3.4.3 Visualization of Plastic Leakage and Fates from the MSWM System

Plastic leakage and fates from the MSWM system was presented using WFD system map and Sankey diagram. In the WFD system map, not only plastic waste flow but also all MSW within the MSWM system was visualized with the number of leaked plastics.

4. Results and Discussions

This research was conducted on the determination of leakage and fates of plastic from the solid waste management chain. First of all, MSWM and MSW flow were presented to estimate household MSW generation and composition, non-households MSW generation, MSW received by sorting or recovery facilities, MSW received by disposal facilities and composition, MSW uncollected, total MSW generation and composition, and waste flow within the MSWM system. Second, plastic leakage potential levels and fate potential levels from the MSWM system were determined according to field observation and then plastic leakage and its eventual fates were estimated based on the conditions of different leakage influencers within the MSWM system and the surroundings using the WFD method. Moreover, potential interventions were recommended for reducing plastic leakage from the MSWM system by testing scenarios. Additionally, microplastic pollution in the water systems is presented the abundance of microplastics in the recognized water systems (canals) in the study area. Also, microplastics were presented to identify forms, size, color, and polymer types.

4.1 Determination of MSW Generation, Composition, and Waste Flow within the MSWM System by WaCT method

4.1.1 Situation of Municipal Solid Waste Management

Solid waste management in Thakhlong town is the responsibility of the municipality office, which includes the collection, transportation, treatment, and disposal of waste. **Figure 7** represents the current waste management activities in the study area. The solid waste generated by residential and commercial areas, excluding industrial waste within the municipal boundary, is collected by 26 waste collection trucks with a capacity of about 5 to 9 m^3. The waste collection trucks are compactors, and the collection routes daily are various depend on the waste generation of the communities in the municipality's responsibility area. The waste collection trucks collect MSW through the roads and the waste collection points. The frequency of waste collection for each community is at least 3 to 6 times per week. Sometimes, solid waste from the areas where alleys and alleys are difficult to access cannot be collected.

In 2021, the amount of average collected MSW was 125 tons, excluding the areas that are hired to collect solid waste from the private sectors such as Talad Thai market and Iyala Market. The collected MSW daily are directly sent to the waste treatment and disposal site owned by Rak Baan Rao Company limited which is hired by the Thakhlong Municipality office. In the waste treatment and disposal site, the solid waste entering the site is firstly sorted for recycling and RDF production, then the organic waste is treated by the mechanical-biological waste treatment (MBT) process, and only the residual waste is landfilled. Therefore, the operations of solid waste management occurred by the municipal office itself are the process of waste collection and transportation and by private companies in pre-disposal and disposal operations.

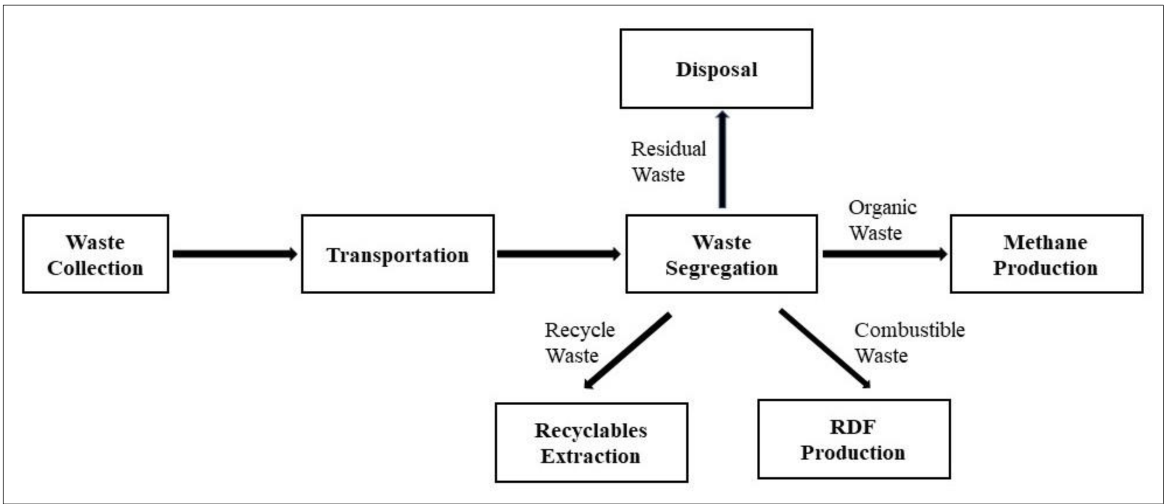


Figure 7: Municipal Solid Waste Management Operations in Thakhlong Town

4.1.2 Municipal Solid Waste Generation

MSW is generated from both households and non-household such as commercial establishments, and various institutions. Therefore, household, and non-household waste generation surveys were conducted for analysis of MSW generation. Household waste generation and composition analysis were conducted by sampling 45 households based on the different housing types for 7 consecutive days during October. Household waste generation and composition were estimated by using the data from the household waste survey in the WaCT excel model, the amount of household waste generated was 53 tons/day.

Figure 8 below presents the average household waste composition. It is found that the maximum proportion of waste composition is organics 60%, the second-largest proportion is plastic 23%, followed by paper, other, and metal and the smallest portion is glass 2%. The amount of waste generation and composition can be changed slightly according to household behavior and seasonal change.

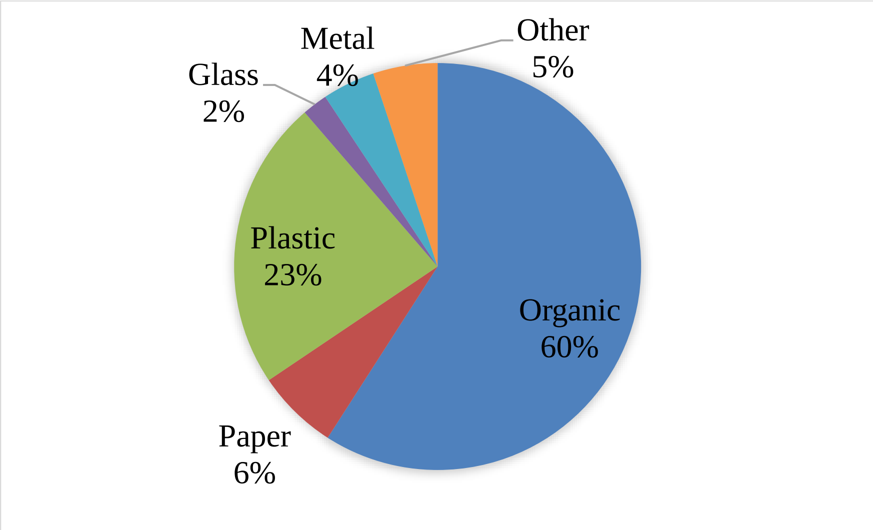


Figure 8: Household Waste Composition

Non-household waste is generated mostly from hotels, restaurants, schools, offices, supermarkets/malls, markets, hospitals, and public spaces. Non-household waste generation analysis was conducted by interviewing the estimated average waste generation daily from at least 1 to 3 premises from the different non-household types directly or their responsible waste collection trucks. In this non-household waste analysis, non-household type for school, the data were collected from only universities as the schools were running the online teaching system during the study period in 2021. The amount of non-household waste was estimated at 77.34 tons/day by using the average non-household waste data from the interview-based survey during the study period (October to December). **Table 7** below shows the summary of the waste generated from the different non-household types estimated with the WaCT excel model.

Table 7: Waste Generation from the Different Non-household Types in Thakhlong

Non-household Type	Number of Non-households	Units		Amount of waste generation (ton/day)
Hotels	11	Rooms	708	1
Restaurants	227	Chairs	25,224	20
University	2	Students (Persons)	29,598	9
Offices	489	Area (sq.m.)	57,221	17
Supermarkets / Malls	30	Area (sq.m.)	8500	10
Markets	13	Stalls	2,045	5
Hospitals	2	Beds	934	4
Public spaces	2	Area (sq.m.)	662140	11
Total				77

Total MSW generation in Thakhlong is found to be around 130 tons/day, which includes household waste generation of about 41 % of total MSW generation and non-households waste generation of about 59% in Thakhlong Town. It is found that the proportion of household and non- households waste amount in Thakhlong town is almost the reverse of the proportion of about 30% of total MSW generated by non-household sources and 70 % by households recommended by the WaCT method (2020) as a default data due to different characteristics of the city (town).

In 2021, the MSW generation rate of Tha Khlong Town was 1.59 kg/capita/day, which was estimated by using the WaCT excel model. In this estimation, the used population number was assumed as 81910 by adding the population from the AIT and Thammasat University dormitories to the original town population of 77104 as AIT and Thammasat University's dormitories are contributing to the MSW generation of Tha Khlong Town. This MSW generation rate is almost the same as the value of 1.5 kg/capita/day shared by the Tha Khlong municipal office and the value of 1.58 kg/capita/day for a higher income level city recommended by the WFD as a last resort.

4.1.3 MSW Disposed and Its Composition

As above mentioned in MSWM, the average MSW collected of around 125 tons/day entered the disposal site owned by Rak Baan Rao Company and then are managed for treatment or pre-disposal, and disposal operations**.** The solid wastes at the site are firstly sorted for recycling about 2% of total MSW, about 30% for Refuse-derived fuel (RDF) production, and organic waste is treated by the mechanical-biological waste treatment (MBT) process for methane production of about 60%, and the residual solid wastes including the rejected waste from RDF and methane production are landfilled. Therefore, the actual amount of MSW disposed of is 8% of the total MSW sent to the landfill although the amount of MSW received by the disposal site is 125 tons/day. The amount of sorting for recycling and disposal amount can be changed sometimes. **Table 8** shows the amount of MSW sorted for recycling, RDF production, and treated for methane production at the disposal facility. The disposal site owned by Rak Baan Rao Company also operates as an energy recovery facility due to RDF and methane production from MSW for electricity production.

Table 8: Amount of MSW Sorted for Recycling, RDF Production, and Treated for Methane Production at Disposal Facility

Type of MSW and Their Utilization		Amount of Waste (ton/day)	Amount of Waste (ton/day)	Amount of Waste (%)
Methane production	Organic Waste	75	75	60
RDF production	Plastic	19	38	30
	Paper	11		
	Other	6		
	Organic waste	2		
Recycling (Sorting)	Plastic	1.4	2	2
	Glass	0.2		
	Metal	0.4		
Landfilling	Residual waste	10	10	8
Total		125	125	100

Components of Municipality solid waste include mostly kitchen waste, garden wastes, paper, cardboard, plastics-film, plastic-dense, textiles, rubber, leather, wood, glass, tin cans, etc. In this study, the data of solid waste samples collected from the MSW of three waste collection trucks were segregated into 6 categories with the quartering method during October. **Figure 9** the maximum proportion of waste composition is organics 52%, the second-largest proportion is plastic 28%, followed by paper 7%, other 6%, and glass 4% respectively and the smallest portion is metal 3%. The MSW disposed composition can be changed depending on the number of sampling trucks and season.

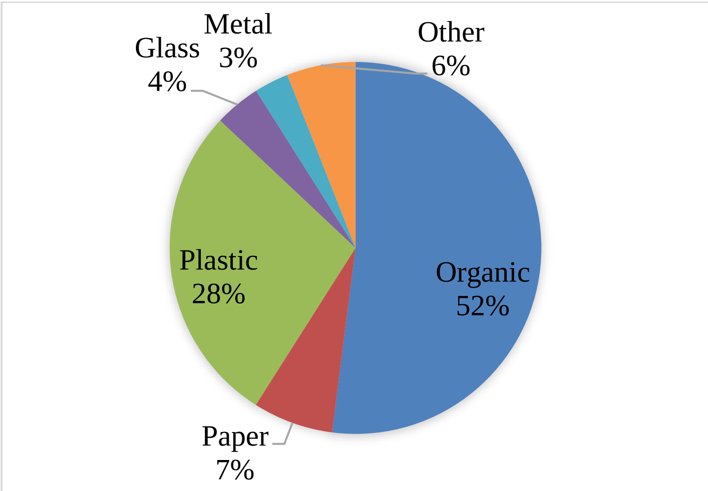


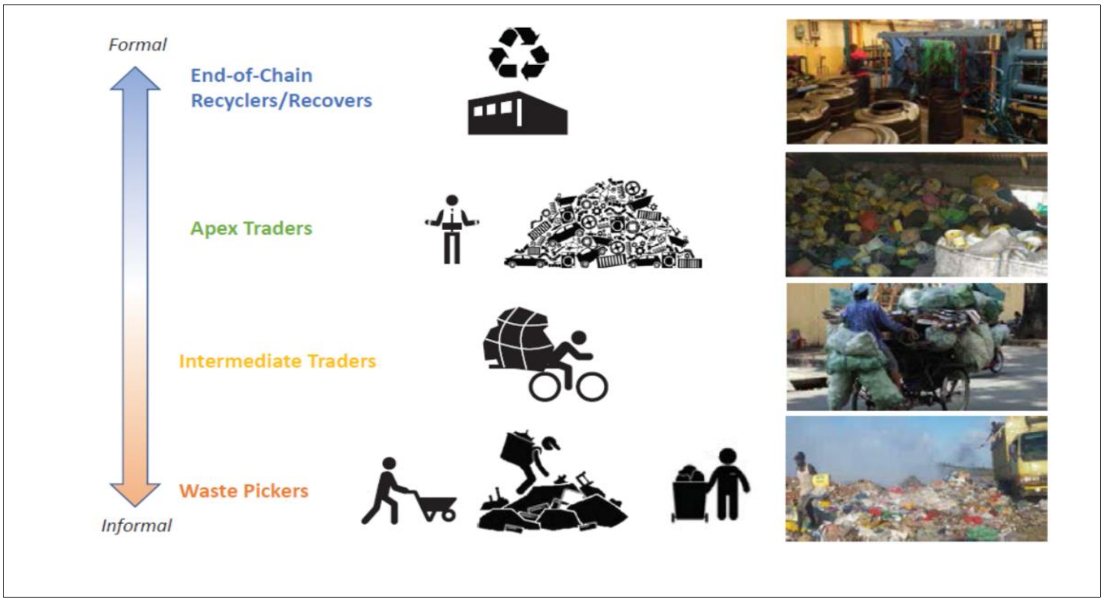
Figure 9: Composition of MSW Disposed of in Thakhlong Town

4.1.4 MSW Sorted by Formal and Informal Sector for Recovery

It is important to identify the MSW sorted by formal and informal sector for recovery since it is an essential part of the total MSW collected. Some of the MSW collected from households and non-household sources are delivered to the recycling firms to sort and recycle. **Figure 10** below shows that the actors of the recovery chain are waste pickers, intermediate traders (tricyclists or the outsider pick-up traders), apex traders (small and medium recycle firms), and end-of-chain recyclers or recovers (big recycle firms or recovery facilities) according to the WaCT.

The formal sector comprises the registered recycling firms, which are apex traders and end-of-chain recyclers or recovers. On the other hand, the waste pickers, the unregistered recycling firms, and the tricyclists or the outsider pick-up traders (intermediate traders). In Tha Khlong, it is observed that some apex traders act as the intermediate traders or the outsider pick-up traders as they buy the recycled materials from households and non-household sources such as company offices with a door-to-door system. In this study, for estimation of the MSW sorted by formal and informal sector for recovery, apex traders are mainly focused since they are observed as the first point of entry into the recovery system. There are 15 registered recycling firms (apex traders) in Tha Khlong. According to the observation and interviews, it is found that the formal sector performance in the recovery system is greater than the informal sector performance in Tha Khlong town.

Due to the limitation of participation of the recycling firms in the research interview, only 7 recycle firms (apex traders) could be interviewed for the required data. The amount of MSW sorted by the left 8 recycle firms was estimated by using the average amount of MSW sorted for a recycle firm calculated from the total amount of MSW sorted by the 7 interviewed recycle firms. The calculation was done for the actual recovery amount and the recovery amount with a proxy estimate for materials loss within the recovery system of 10% according to the WaCT methodology. In the calculation of recovery amount from both formal and informal sectors, the recovery amount from the informal sector was calculated by using about 30% of the total recovery amount according to the interview recycle firms and information. The amount of MSW sorted by formal and informal sector for recovery and the recovery amount with a proxy estimate for materials loss within the recovery system of 10% according to the assumption of the WaCT method are shown in **Table 9** and **Table 10**. The difference between the actual recovery amount and the recovery amount with a 10% reject rate can be seen clearly in **Figure 11** described in the next section **4.1.5 MSW Flow Thakhlong Town**.



Source: Waste Wise Cities Tool (2021)

Figure 10: Formal and Informal Sector in the Recovery Chain

Table 9: MSW Sorted by Formal and Informal Sector for Recovery

Type of Recovery	Type of MSW Recovered and Their Amount (kg)						Total
	Glass	Metal	Organic	Other	Paper	Plastic	
Energy Recovery (Formal)	0	0	77	6	11	19	113
Material Recovery (Formal)	0.28	0.62	0.00	0.00	0.73	0.34	1.97
Material Recovery (Informal)	0.66	1.44	0.00	0.00	1.71	0.79	4.59
Total	0.94	2.06	77.00	6.00	13.44	20.13	119.57

Table 10: MSW Sorted by Formal and Informal Sector for Recovery with a proxy estimate of 10 % materials loss within the recovery system

Type of Recovery	Type of MSW Recovered and Their Amount (kg)						Total
	Glass	Metal	Organic	Other	Paper	Plastic	
Energy Recovery	0.00	0.00	69.30	5.40	9.90	17.10	101.70
Material Recovery (Formal)	0.25	0.56	0.00	0.00	0.66	0.30	1.77
Material Recovery (Informal)	0.59	1.30	0.00	0.00	1.54	0.71	4.13
Total	0.84	1.85	69.30	5.40	12.09	18.11	107.60

4.1.5 MSW flow in Thakhlong Town

Figure 11 below depicts the MSW flow in terms of MSW generation both households waste generation and non-household waste generation, MSW recovered, MSW disposed of, and MSW uncollected in Tha Khlong, Thailand of 81910 inhabitants. Results show that 130 tons/day of MSW is generated, of which 91 % is collected and managed in controlled facilities. The city recovery rate is 83 % and around 12 t/day remain uncollected. Additionally, according to the WaCT excel model calculation, it was found that the food waste generation rate in Tha Klong was 0.36 kg/capita/day.

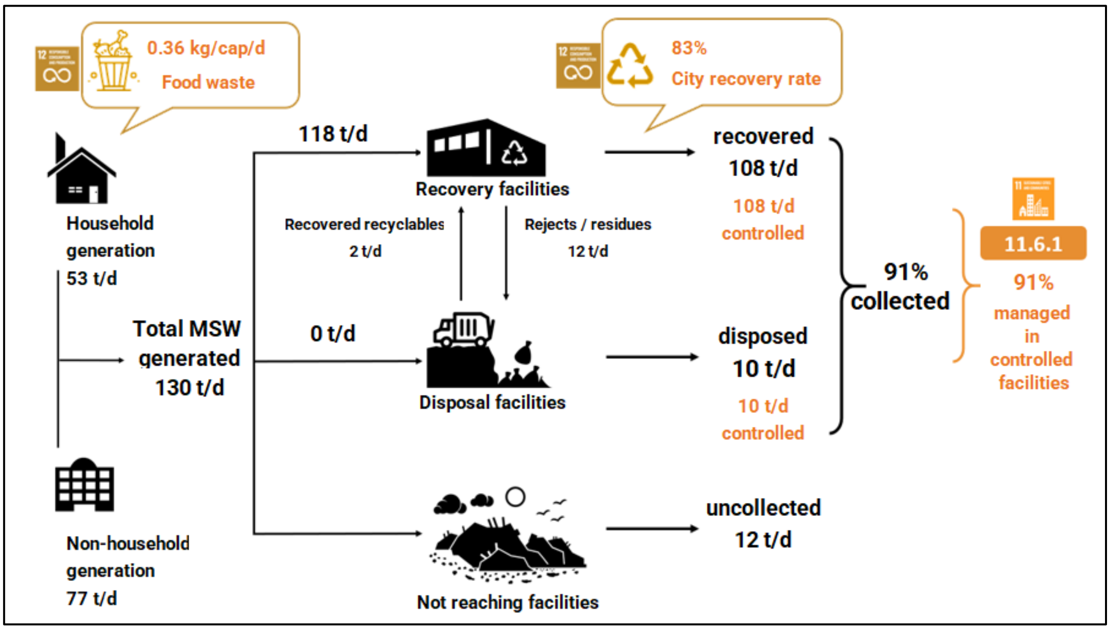


Figure 11: MSW Flow in Thakhlong Town.

4.1.5 Municipal Solid Waste Composition

Analysis of overall MSW composition is important for the investigation of plastic leakage and its fates from the solid waste management chain to achieve accurate data. In this study, therefore, MSW composition is calculated by using the amount of waste per fraction of MSW recovered, disposed of, uncollected, and extracted from disposal sites based on the methodology of WFD shown in **Table 11** and **Figure 12**. In this study area, the maximum proportion of waste composition is organics 64%, the second-largest proportion is plastic 18%, followed by paper 10%, other 5%, and metal 2% respectively and the smallest portion is glass 21%. In this calculation, waste fractions for MSW uncollected were assumed same as the composition of a household waste composition according to the guidelines of the WFD methodology.

Table 11: Calculation of Overall MSW Composition

Types of MSW and Units	Glass	Metal	Organic	Other	Paper	Plastic	Total
MSW recovered (ton/day)	0.34	1.86	69.56	5.42	12.14	18.18	108.00
MSW disposed (ton/day)	0.48	0.36	6.24	0.72	0.84	3.36	12.00
MSW uncollected (ton/day)	0.24	0.48	7.20	0.60	0.72	2.74	12.00
Extracted from disposal sites (ton/day)	0.200	0.400	0	0	0	1.4	2.000
Total MSW (ton/day)	0.86	2.30	83.00	6.74	13.70	22.89	130.00
MSW composition (%)	1.00%	2.00%	64.00%	5.00%	10.00%	18.00%	100.00%

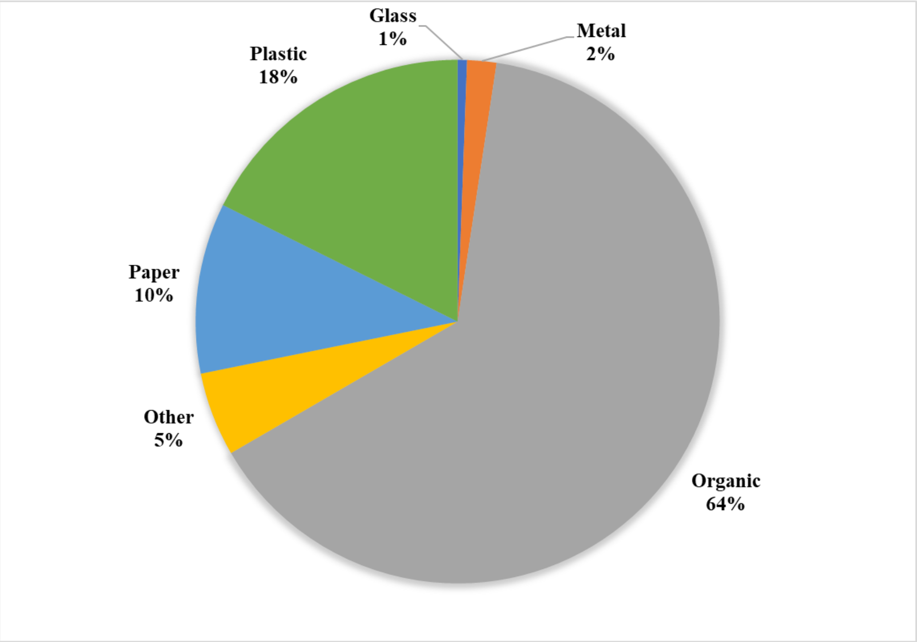


Figure 12: MSW Composition

4.2 Estimation of Plastic Leakage from the MSWM System and Fates of Plastic Leakage (Plastic Pollution per Fate) by WFD Method

For estimation of plastic leakage from the MSWM system and fates of plastic leakage in Thakhlong Town, firstly, it is necessary to determine leakage potential levels from the stages of the MSWM System such as collection, transportation, and disposal stages, etc. and fate potential levels for different leakage types. Leakage potential levels and fate potential levels were determined by the assessment based on the findings of field observation and information about the MSWM in Thakhlong based on the WFD method.

4.2.1 Determination of Plastic Leakage Potential Levels within the MSWM System

4.2.1.1 Plastic Leakage Potential levels from Collection Services. Plastic can escape into the environment from the MSWM system especially during storage in collection containers, loading onto the collection vehicles, transportation, and handling waste. For estimation of plastic leakage from collection services with the WFD method, it is necessary to determine leakage potential levels for different leakage influencers of collection services by field observations conducted in the vicinity of the collection services and interviewing the residents and collection service workers. The collection containers, loading method, primary transportation, and multiple handling were considered as leakage influencers for plastic leakage from collection services.

In Thaklong, regarding the collection containers, it was observed that most waste containers looked like that shown in **Figure 13 (A)** and therefore are typically no lids, show low levels of damage, and are not easily accessible by animals. The capacity of the bins is generally sufficient for the quantity of waste but some dumping of waste around the collection container may occur. It was found that waste is occasionally disposed of in bags and containers are available in most districts. It was known that the frequency of collection is slightly below what is required, and service is occasionally delayed beyond the minimum frequency. According to the facts from field observations and interviews in the study area, the assessment was deemed to best fit the “low” leakage potential level for leakage influencer “collection containers” by using the corresponding descriptive table for the determination of leakage potential level for leakage influencer “collection containers” described in WFD user manual.

Moreover, most of the loading methods looked like that shown in **Figure 13 (B),** and thus waste was manually loaded into vehicles. The storage containers are generally portable and are transported to the waste collection vehicle with the waste still inside. Due to the facts from field observations and interviews in the study area, the “medium” leakage potential level for the influencer “loading method” was assessed by using the corresponding descriptive table for the determination of the leakage potential level for leakage influencer “loading method” described in WFD user manual.

In field observations regarding primary transportation, it was found that the collected wastes are immediately transferred to the disposal site. Therefore, the leakage potential level for influencer “primary transportation” was deemed to best fit as “none” with the corresponding descriptive table for determination of leakage potential level for leakage influencer “primary transportation” described in the WFD user manual.

Regarding multiple handling, as there is no distinction between primary and secondary collection and no multiple handling, the leakage potential level for influencer “multiple handling” was deemed to best fit as “none” with the corresponding descriptive table for determination of leakage potential level for leakage influencer “multiple handling” described in WFD user manual.

Figure 13: Situation of Collection Services (A) Collection containers, and (B) Loading Method.

4.2.1.2 Plastic Leakage Potential Levels from Informal Value-Chain Collection. Plastic can escape into the environment while the wastes are being collected and transported by the informal sector. For estimation of plastic leakage from the informal value-chain collection with the WFD method, it is necessary to determine leakage potential levels for different leakage influencers of informal value-chain collection by field observations conducted around the surroundings in Thaklong and interviewing the waste pickers. The extraction method of recycles and transportation method were considered as leakage influencers for plastic leakage from the informal value-chain collection.

In Thaklong, it was observed that most waste pickers looked like that shown in **Figure 14 (A)** Most of the plastic materials are separately collected from the sources such as canals and waste containers roadside and therefore the informal sector was assumed to cause little to no release of waste into the environment during collection. Moreover, practices such as overturning bins to get access to valuable material and discarding unwanted items during the collection were rare as waste pickers collected their wanted valuable waste only. Moreover, most waste pickers' vehicles looked like that shown in **Figure 14 (B)** and therefore informal sector used to transport plastic waste is closed to the environment (i.e., cover) and most vehicles stay within their capacity limit.

According to the observations and interviews in the study area, the assessments were deemed to best fit the "low" leakage potential for influencer "extraction method of recycles", and the "low" leakage potential for influencer "transportation method" according to the corresponding descriptive tables of the leakage potential for different leakage influencers of informal value-chain collection described in WFD user manual.

Figure 14: Situation of Informal Value chain Collection (A) extraction method of recycles, and (B) Transporation Method.

4.2.1.3 Plastic Leakage Potential Levels from Formal Sorting. Plastic can leak into the environment from the waste rejected by formal sorting facilities which might be dumped or mismanaged. For estimation of plastic leakage from collection services with the WFD excel model, it is necessary to determine leakage potential levels for leakage influencers of formal sorting by observing, and assessing the surrounding conditions around the formal sorting facilities. In this case, it is assumed that the plastic rejects rate is 10% of the total amount of formally collected plastic as an assumption of the WaCT method mentioned in the previous section **4.1.5**. For this case, the disposal of rejects for formal sorting facilities was only considered as a leakage influencer.

In Thaklong, most formal sorting facilities or recycling firms looked like that shown in **Figure 15,** and therefore most of the sorting rejects are returned to the formal waste collection system (containers) in the vicinity and are regularly serviced. Therefore, most dumping or open burning of waste is not believed to have originated from formal sorting activities.

According to the observations in the study area, the assessments were deemed to best fit the “low” leakage potential for influencer “disposal of rejects”, according to the corresponding descriptive tables of the leakage potential for different leakage influencers of formal sorting described in WFD user manual.

Figure 15: Situation of Disposal of Rejects from Formal Sorting Facilities

4.2.1.4 Plastic Leakage Potential Levels from informal service-chain sorting. Plastic can escape into the environment from the waste rejected during informal service-chain sorting which might be dumped or mismanaged. This case considered only the service-chain branch of the informal sector (i.e., informal waste collection service) and did not consider the informal value-chain as waste pickers collecting valuable materials are automatically sorting waste (i.e., informal sorting) as they pick by collecting only valuable waste, not collecting valueless waste. Therefore, it was assumed that any leakages associated with informal service-chain sorting are instead assigned to the collection phase. In Thaklong, no informal service chain (i.e., informal waste collection service) was assumed, and consequently no disposal of reject and reject rate. As a result, there is no plastic leakage from informal service-chain sorting in this area.

4.2.1.5 Plastic Leakage Potential Levels during transportation to disposal. Plastic can leak into the environment from the MSWM system when the wastes are being transported by collection vehicles to their final destination. For estimation of plastic leakage during transportation to disposal with the WFD method, it is necessary to determine leakage potential levels for leakage influencers during transportation to disposal by field observations conducted in the vicinity regarding waste collection, transportation to disposal, and interview waste collection service workers from waste collection trucks. The leakage influencers, capacity and load, waste containment, and vehicle cover during transportation to disposal were considered as leakage influencers.

In this study area, around half of the transportation, vehicles were running over capacity sometimes but the waste was being collected and transported in bags as shown in **Figure 16 (A).** Most of the generators in the city dispose of their waste contained in bags as shown in **Figure 16 (B).** Most of the collection vehicles in the city looked like compactor trucks and therefore are fully enclosed as shown in **Figure 16 (C).**

Therefore, the "medium" leakage potential for influencer "capacity and load", the "low" leakage potential for influencer "waste containment", and the "medium" leakage potential for influencer "vehicle cover" were determined by using the corresponding descriptive tables of the leakage potential level for different leakage influencers during transportation to disposal described in WFD user manual.

Figure 16: Situation of Collection vehicles (A) Capacity and Load, (B) Waste Containment, and (C) Vehicle Cover during Transporation to Disposal

4.2.1.6 Plastic Leakage Potential Levels from Disposal Facilities. Plastic can leak into the environment from disposal sites carried either by the wind or by water/landslides. For estimation of plastic leakage from disposal facilities with the WFD method, plastic leakage potential levels for leakage influencers from disposal facilities were determined services by field observations conducted in the vicinity of the disposal site and interview the owner of the disposal site. The environmental hazards, exposure to weather, waste handling, coverage, burning, and fencing were considered leakage influencers regarding the disposal site.

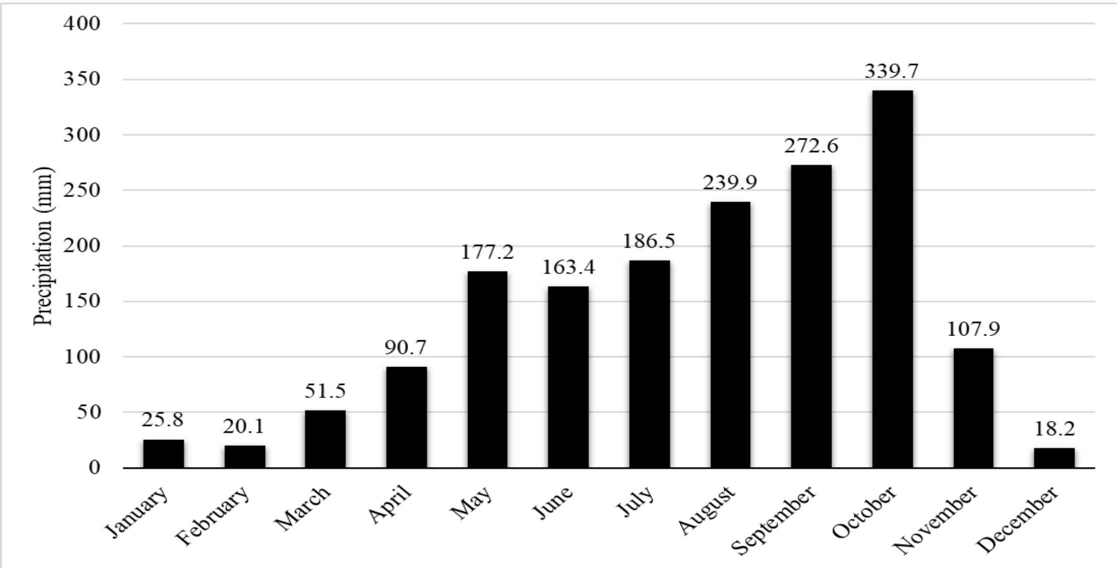
According to field observation and information, the disposal site had experienced flooding in 2011 only once. It had never experienced landslides as it is in an area without the potential for landslides as shown in **Figure 17 (A)**. Therefore, it was assumed that the disposal site is in an area that does not regularly have environmental hazards such as flooding or landslides. The site was sometimes exposed to heavy and persistent winds or surface runoff. The site has recovery options for waste such as RDF production and methane production and operates not only a disposal facility but also a recovery facility. Therefore, at the site, waste was discharged in a designated area as shown in **Figure 17 (B)** and waste pickers were not allowed on site. The workers of the site are sorted the recyclable materials for recycling and RDF production, and organic waste for methane production. Therefore, the management of waste occurs on the site. After sorting, only the residual wastes are disposed of. Most of the waste is under minimal exposure to wind, rain, and surface runoff. It was known that the site has occurred no coverage and no burning. It was observed that a fence surrounds less than half of the perimeter shown in **Figure 17 (C).**

Therefore, the assessments were deemed to best fit the “none” leakage potential for influencer “environmental hazards”, the “medium” leakage potential for influencer “exposure to weather”, the “low” leakage potential for influencer “waste handling”, the “very high” leakage potential for influencer “coverage”, the “very high” leakage potential for influencer “burning”, and the “high” leakage potential for influencer “fencing” according to the descriptive tables related to leakage influencers of disposal facilities described in WFD user manual.

Figure 17: Situation of Disposal Site (A) Site Location, (B) Waste Handling, and (C) Fencing

4.2.1.7 Plastic Waste in Storm Drains Entering Waterways. Plastic is transferred through storm drain systems and enters water systems. In this study, it is assumed that any plastic not removed from the drains by cleaning is eventually transferred to waterbodies. As rainfall dictates when this plastic will become mobile within the drains, the more frequent the rainfall, the less opportunity there is to remove the waste before it gets washed into waterbodies. It was considered that frequency of rainfall/storms, and drain cleaning as the leakage influencers for this case.

In consideration of leakage influencer "frequency of rainfall/storms", it is known that Tha Khlong Town has three seasons, winter from mid-October to mid-February, the summer from mid-February to mid-May, and the rainy season from mid-May to mid-October with heavy rainfall. The dry period is from December to February with less rainfall while December is the driest month of the year. The average annual precipitation total is 1652.8 mm and the average precipitation in the driest month December is 18.2 mm less than 60 mm (WORLD WEATHER ONLINE, 2021). Therefore, the climate of the study area is classified as the tropical savanna climate (Aw) because it is classified tropical savanna climate (Aw) of precipitation in the driest month is less than 10 cm and less than 4% of total annual precipitation according to Köppen climate classification (EarthHow, 2022) shown in **Figure 18**. Additionally, as the climate of Pathum Thani Province is a Tropical savanna climate (Aw) (CLIMATE-DATA.ORG, 2022), it can be assumed that Thaklong's climate is also a Tropical savanna climate (Aw). During observation and interview regarding the drainage system, it is found that Klong Naung and Klong Song canals and some drains are cleaned once per year as shown in **Figures 19 (A)** and litter traps are not used for the drain outlets, which can be seen in **Figures 19 (B)**. Therefore, the assessments were deemed to best fit the "low" leakage potential for influencer "frequency of rainfall/storms", and the "high" leakage potential for influencer "drain cleaning" according to the descriptive tables of the leakage potential for different leakage influencers of plastic waste in storm drains entering waterways described in WFD user manual.



Source: (WORLD WEATHER ONLINE, 2021)

Figure 18: Average Rainfall of Tha Khlong Town

Figure 19: (A) Drainage Cleaning and (B) Drain Outlet without Litter Trap

4.2.2 Determination of Fate Potential Levels for Different Leakage Types

4.2.2.1 Fate potential levels for diffuse voluntary leakage. The leakage type "diffuse voluntary" represents the dumping of land, drains, and water systems and the open burning of waste from uncollected waste under someone's control. Field observations were conducted in the areas without getting enough waste collection frequency or the areas where is difficult to access waste collection, where cannot be collected the waste sometimes.

In Thaklong, in the areas without getting enough waste collection frequency or the areas where is difficult to access waste collection, where cannot be collected the waste sometimes, it was assumed that a few residents may have occasionally burnt waste looked like that shown in **Figure 20 (A)**, however, this is believed to be a rare occurrence. There is sporadic evidence that a minority of residents may regularly dump their waste on land and drains looked like that shown in **Figures 20 (B) and (C)**, but this is not assumed to be the primary means of disposal for most residents. Moreover, few residents are close (<500 m) to water systems to which they have access as shown in **Figure 20 (D).**

According to the field observations in the study area, the assessments were deemed to best fit the "very low" fate potential for "open burning", the "low" fate potential for "land", the "very low" fate potential for "drains", and the "very low" fate potential for "water systems" according to the corresponding descriptive tables for the fate potential levels regarding diffuse voluntary described in WFD user manual.

Figure 20: Disposal options (A) open burning, (B) dumping on land, (C) dumping on drains, and (D) human settlement close to the water systems in the areas without getting enough waste collection

4.2.2.2 Fate potential levels for diffuse involuntary leakage. The leakage type "diffuse involuntary" represents plastic that is released to the environment from many locations whilst not under someone's control. Therefore, observation assessments were done in multiple locations throughout the study area.

In Thaklong, major parts of the study area (near main roads) show little evidence of plastic waste on land while there is evidence of small quantities of plastic remaining on land in minor areas (alley areas) like that shown in **Figure 21 (A) and (B)**, small quantities of plastic in drains as shown in **Figure 21 (C)**. Vegetation on the banks of the water systems is very sparse throughout major parts of the study area, which can be seen in **Figure 21 (D)** and almost all of the study area is close (<1 km) to water systems like that shown in **Figure 22.**

According to the observations in the study area, the assessments were deemed to best fit the “very low” fate potential for “land”, the “very low” fate potential for “drains”, and the “high” fate potential for “water systems” according to the corresponding descriptive tables for the fate potential levels regarding diffuse involuntary described in WFD user manual**.**

Figure 21: Situation of (A) Plastic Remaining on Land (major area) (B) Plastic Remaining on Land (minor area), (C) Plastic Remaining in Drain, and (D) Vegetation on the Banks of the Water System (Canal) in Thaklong

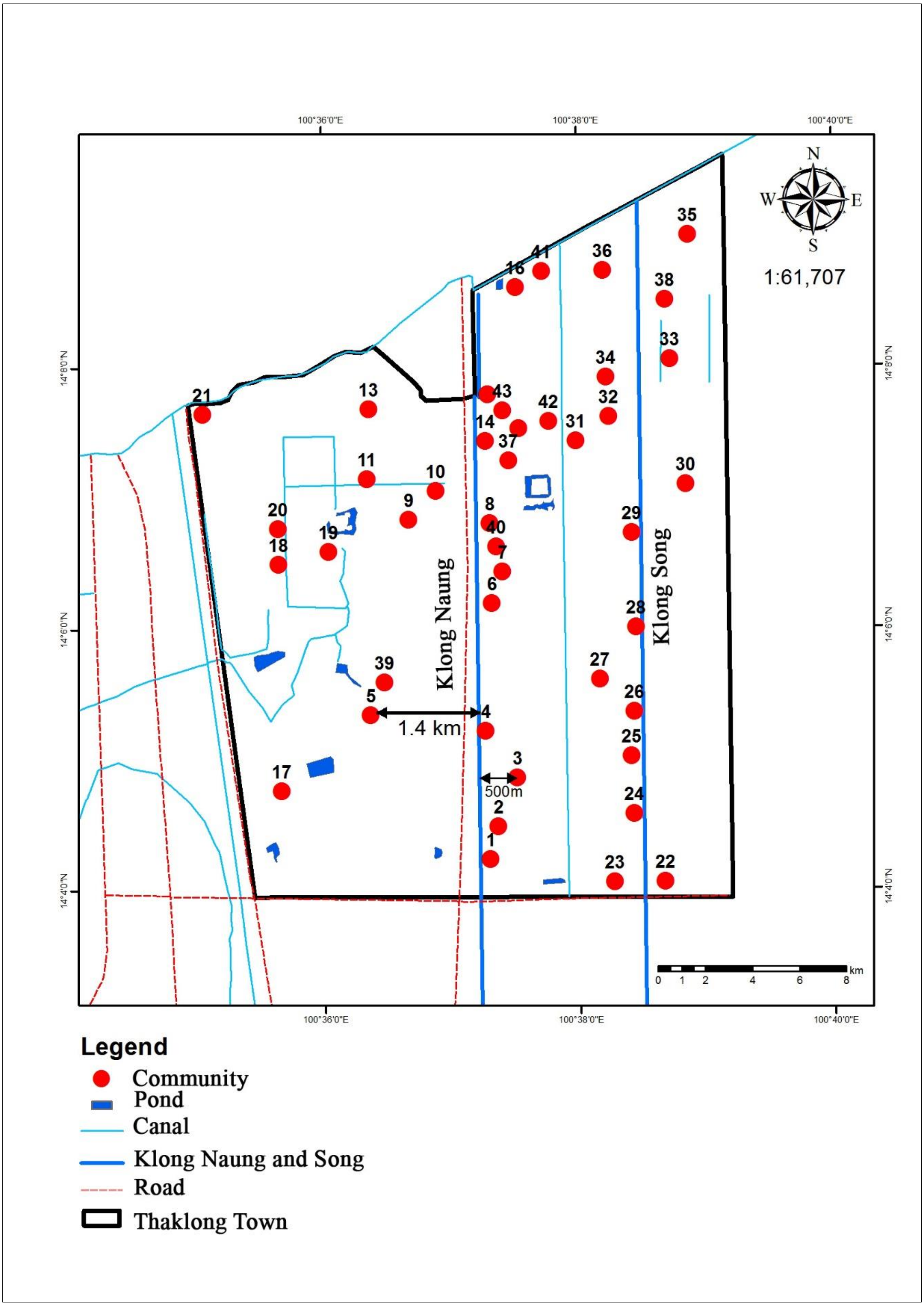


Figure 22: Map showing the study area close to water systems (<1 km)

4.2.2.3 Fate potential levels for point source voluntary leakage type. The leakage type "point source voluntary" represents plastic rejects that are burnt or dumped on the land, drains, and water systems from sorting facilities as a disposal option. In this case, the small recycling firms are assumed as sorting facilities as the small recycling firms mainly operate sorting activities and they are the first point of entry into the recovery system. Therefore, observation assessments were done in the vicinity of sorting facilities throughout the study area.

During the field observation within the study area, it is assumed that sorting facilities may not have openly burned their sorting rejects and dumped their sorting rejects on land and drains. However, most sorting facilities are close (<500 m) to water systems to which they have access as shown in **Figure 23**.

According to the field observations in the study area, the assessments were deemed to best fit the "none" fate potential for "open burning", the "none" fate potential for "land", the "none" fate potential for "drains", and the "high" fate potential for "water systems" according to the corresponding descriptive tables for the fate potential levels regarding point source voluntary described in WFD user manual.

4.2.2.4 Fate potential levels for point source involuntary leakage type. The leakage type "point source involuntary" represents plastic that is released to land, drains, and water systems from the disposal facilities. Therefore, observation assessments were done in the vicinity of disposal facilities in the study area.

Near the disposal site, there is evidence that some areas show evidence of large quantities like that shown in **Figure 24 (A),** and small quantities of plastic entering can be seen in **Figure 24 (B)**. The disposal site is very close (<1 km) to water systems and vegetation on the banks of the water systems are sparsely shown in **Figure 25**.

According to the observations in the study area, the assessments were deemed to best fit the "very low" fate potential for "land", the "very low" fate potential for "drains", and the "high" fate potential for "water systems" according to the corresponding descriptive tables for the fate potential levels regarding point source involuntary described in WFD user manual.

Figure 24: Situation of (A) Plastic Remaining on Land, and (B) Plastic Remaining in Drain near the Disposal Site

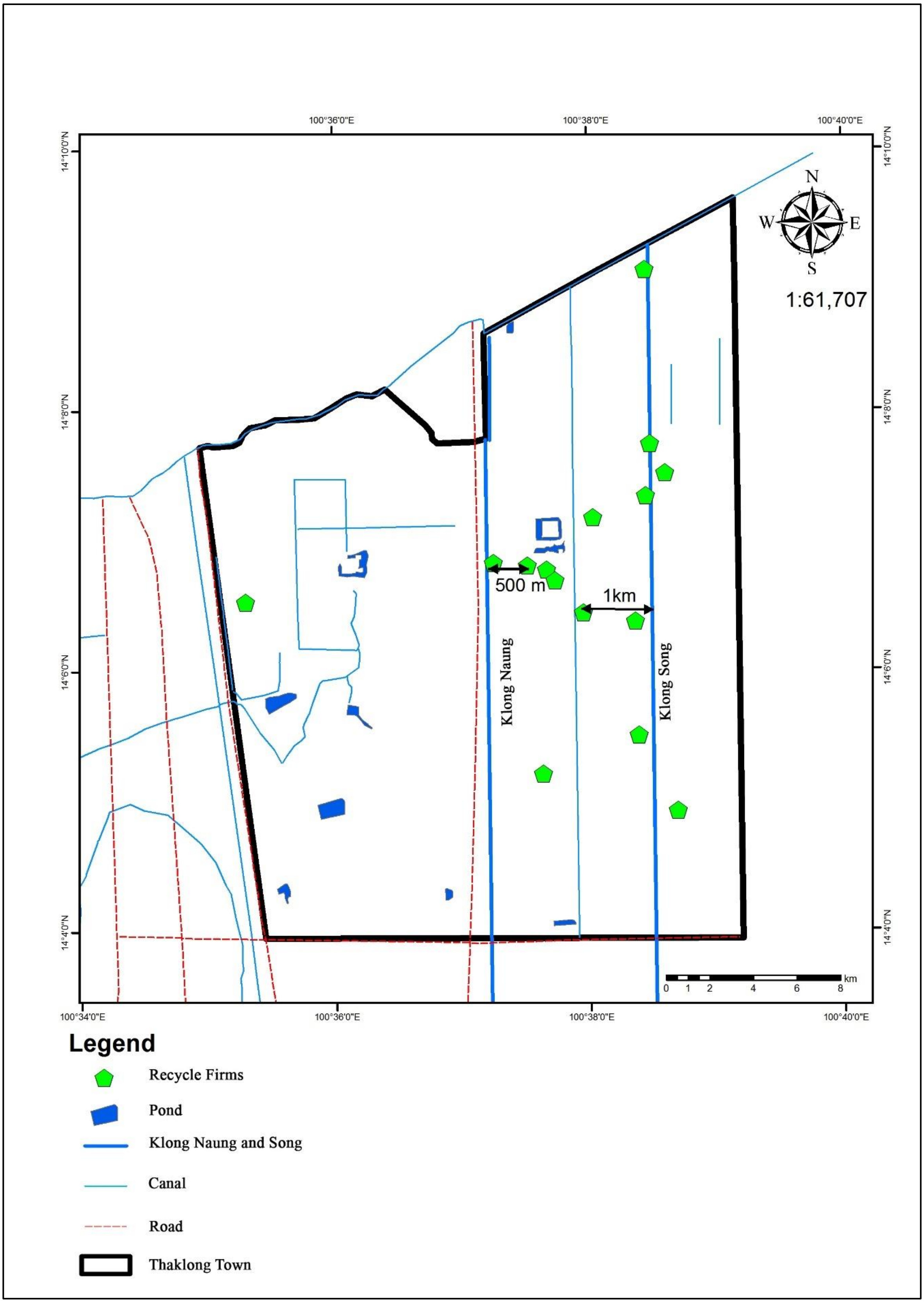


Figure 23: Map showing sorting facilities (recycle firms) close to water systems (< 500 m)

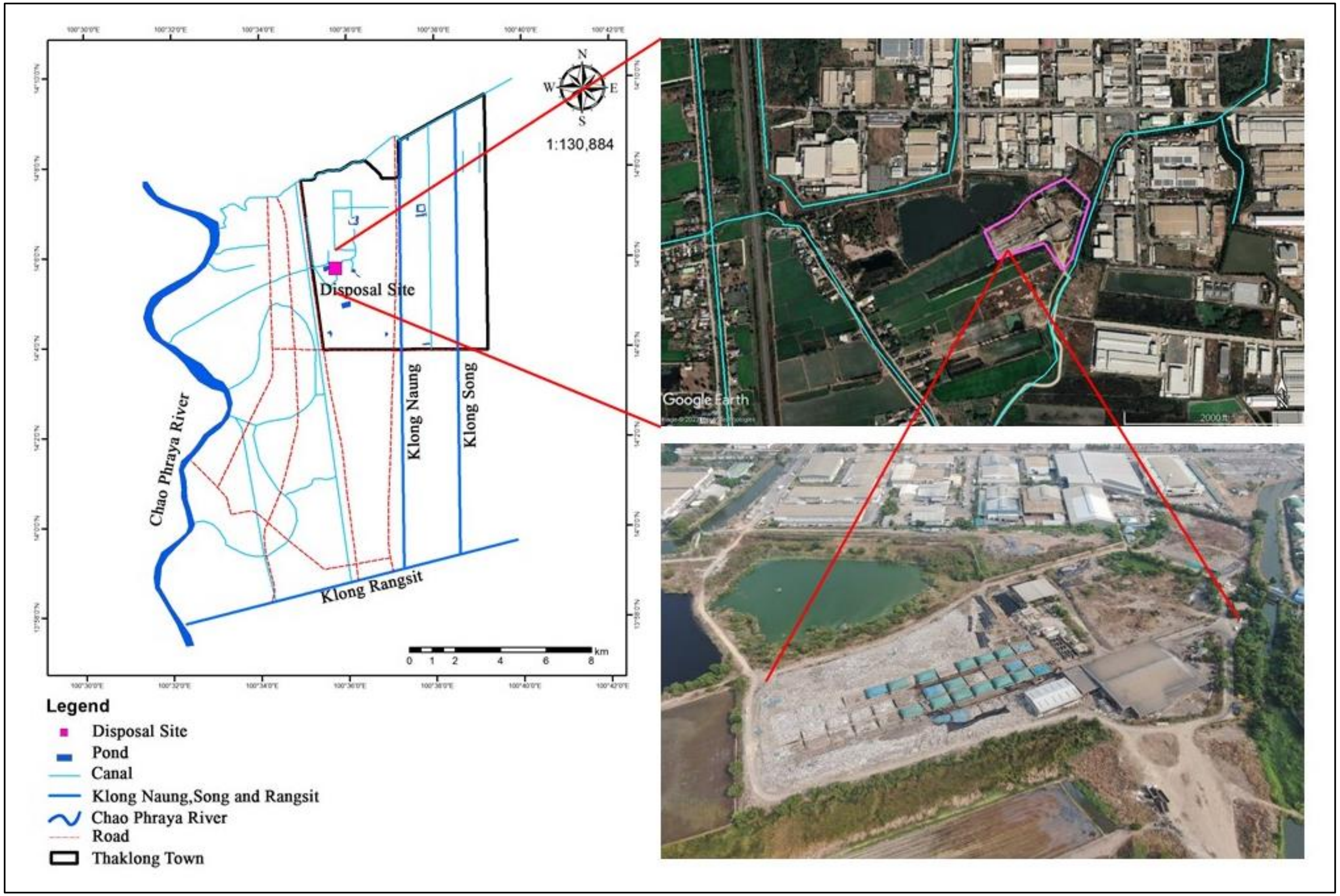


Figure 25: Map showing disposal facilities very close to water systems

4.2.3 *Plastic Leakage from the MSWM System and Fates of Plastic Leakage (Plastic Pollution per Fate)*

The plastic leakage and the fates of mismanaged plastic waste into the environment were estimated by using MSWM data and field observations with the WFD excel-based model that can calculate the contribution amount of plastic leakage from the MSWM system and the amount of plastic potential leakage into the environment.

Table 12 gives a summary of MSW, plastic waste generation, and their management. Plastic waste 34 tons includes 130 tons of total MSW generation. About 10% of all plastic waste is not collected. This corresponds to 839 tons of uncollected plastics per year compared to 8,557 tons generated. Disposal amount is relatively low with only 12% of energy recovery from waste is 73 % of plastic waste generation. the amount of waste sorted for recovery including 3% from informal sorting and 1% from the formal sorting system

Table 12: MSW and Plastic Waste Management Results

Description	MSW	Plastic Waste	Unit
Municipal solid waste generation	47,536	8,557	Tons/year
Municipal solid waste generation	130	23	Tonnes/day
Collected waste	43,013	7,717	Tonnes/year
Collected waste	90%	90%	% of waste generation
Uncollected waste	4,524	839	Tonnes/year
Uncollected waste	10%	10%	% of waste generation
Waste sorted for recovery *(excludes energy from waste)*	2,157	369	Tonnes/year
Waste sorted for recovery *(excludes energy from waste)*	5%	4%	% of waste generation
Waste sorted for recovery by formal sector *(excludes energy from waste)*	3%	3%	% of waste generation
Waste sorted for recovery by the informal sector *(excludes energy from waste)*	1%	1%	% of waste generation
Energy from waste	37,121	6,242	Tonnes/year
Energy from waste	78%	73%	% of waste generation
Disposal in disposal facilities	3,650	1,022	Tonnes/year
Disposal in disposal facilities	8%	12%	% of waste generation

The following **Table 13** shows the estimated fates of unmanaged plastic waste. Unmanaged plastic waste is a combination of uncollected waste as displayed in the Table above and plastic leakages from waste management operations such as collection, treatment, and final disposal.

Table 13: Plastic Leakage from MSWM System and Fate of Plastic Waste Results

	Plastic Waste	**Unit**
Unmanaged plastic waste	926	Tonnes/year
Unmanaged plastic waste	11%	% of plastic waste generation
Contribution from uncollected waste	90.67%	% of mismanaged plastic waste
Contribution from collection service	9.04%	% of mismanaged plastic waste
Contribution from informal value-chain collection	0.01%	% of mismanaged plastic waste
Contribution from formal sorting	0.14%	% of mismanaged plastic waste
Contribution from informal sorting	0.00%	% of mismanaged plastic waste
Contribution from transportation	0.00%	% of mismanaged plastic waste
Contribution from disposal facilities	0.14%	% of mismanaged plastic waste
Plastic waste retained on land	511	Tonnes/year
Plastic waste retained on land	55%	% of mismanaged plastic waste
Plastic waste openly burnt	120	Tonnes/year
Plastic waste openly burnt	13%	% of mismanaged plastic waste
Plastic waste cleaned from drains	11	Tonnes/year
Plastic waste cleaned from drains	1%	% of mismanaged plastic waste
Plastic waste to water systems	284	Tonnes/year
Plastic waste to water systems	31%	% of mismanaged plastic waste
Plastic waste to water systems	3%	% of plastic waste generation
Contribution directly entering water systems	56%	% of plastic in water systems
Contribution entering via storm drains	44%	% of plastic in water systems

Applying the WFD for this study area delivers the results presented in **Table 4.9** above. These are based on a detailed assessment of leakage influencers and fates for leaked plastics according to information and findings from field observations collected as mentioned in the former section. The results show clearly that the main contribution to unmanaged waste from uncollected waste is 90.67% and that other leakages are comparatively insignificant as a contribution from collection service is 9.04%, 0.01% from the informal value-chain collection, 0.14% from formal sorting with no contribution from informal sorting and transportation.

Based on the observations in the field most of the uncollected waste is retained on land 55%, while some are either burned or accumulated in drains. The potential leakage to waterways is estimated to be around 31 % of unmanaged plastic waste. Due to the large amount of plastic waste generated, weak collection services, and the study area located near waterways, this still accumulates to 284 tons/year in the water systems. 284 tons of plastic waste or 4% of the total plastic waste is estimated to enter the waterways such as Klong Naung and Klong Song in the study area from municipal solid waste sources.

Figure 26 gives an overview of the total amounts of MSW and plastic waste, and their flow within the MSWM system briefly in Tha Klong Town in tons per year. Sankey diagram **Figure 27** gives a visual representation of the situation of plastic leakage and plastic pollution per fate with the plastic waste management situations in Tha Khlong Town.

Moreover, applying the WFD delivers the estimation of plastic pollution per capita in this study area with some assumptions presented in **Table 14**. The table shows that each person in Thaklong town releases 3.5 kg of plastic waste that enters waterways per year. This is equivalent to 116 PET plastic bottles released per person per year, 3 Olympic swimming pools per year, and 418 waste trucks with 20 m^3 per year.

Table 14: Estimation of Plastic Waste Generation Rate

Description	Amount of Plastic Waste	Unit
Plastic to water systems per person	3.5	kg per person/year
Plastic to water systems per person	116	no. PET bottles per person/year*
Plastic to water systems	3	no. of Olympic swimming pools/year**
Plastic to water systems	418	no. of waste trucks/year***

*Mass of 1.5 litre PET bottle: 30 g
**Pool volume: 2,500 m^3, Density mixed plastic waste: 34 kg/m^3
***Volume truck: 20 m^3, Density mixed plastic waste: 34 kg/m^3

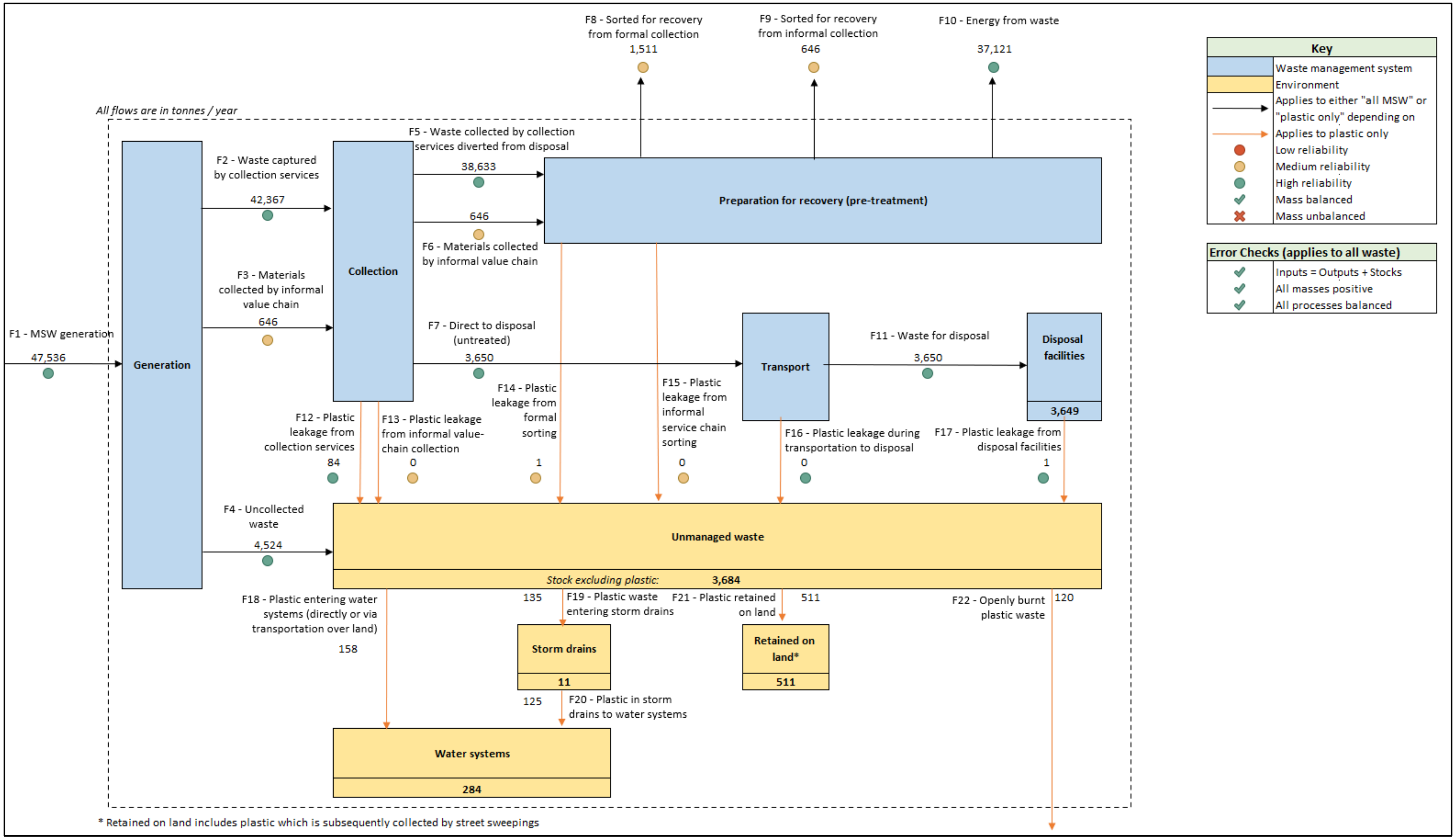


Figure 26: Waste Flow Diagram for all MSW and Plastic Waste

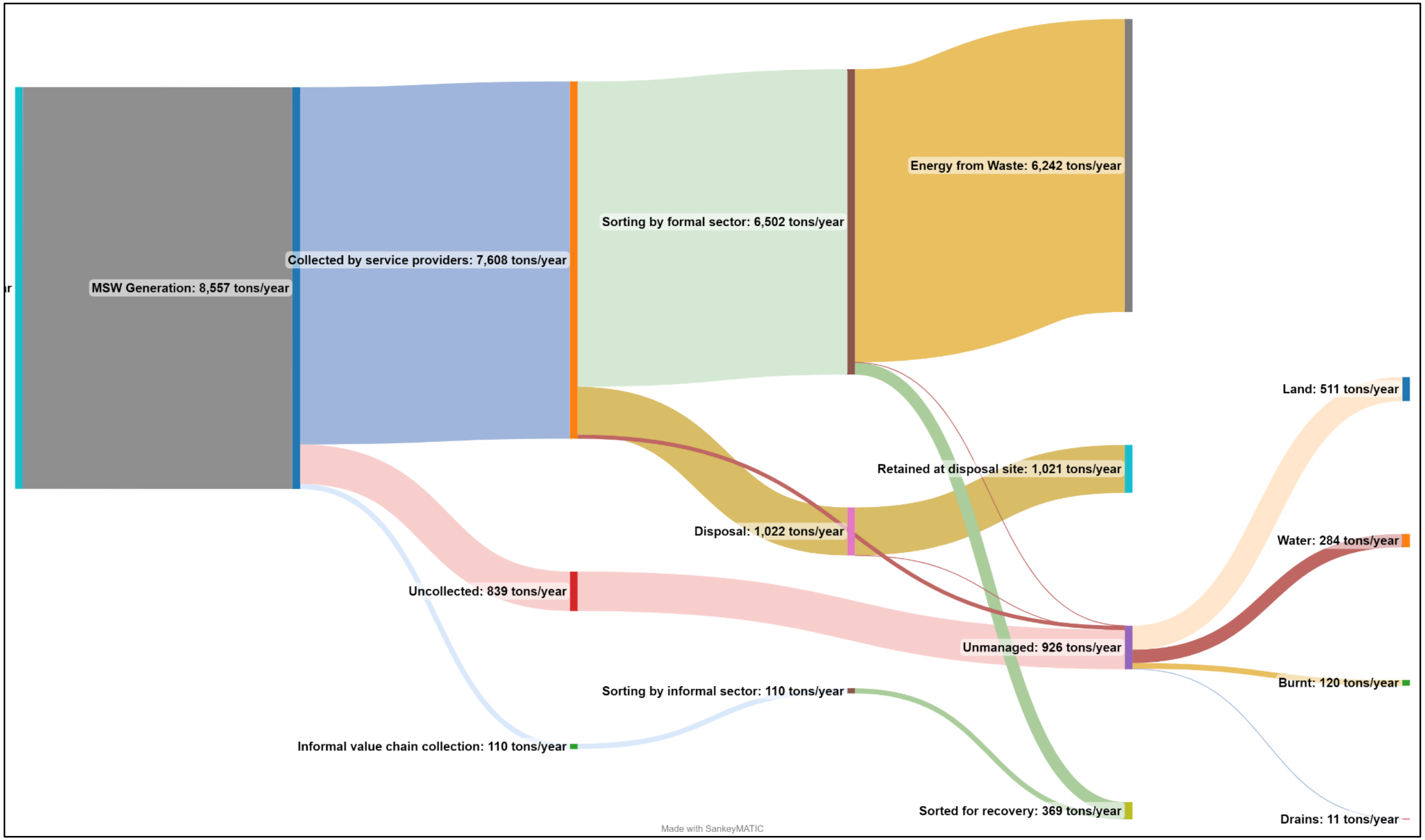


Figure 27: Plastic Waste Flow Diagram Showing Plastic Leakage and Fates of Plastic Leakage (Sankey Diagram)

5. Conclusions

In Thaklong, the MSW generation rate was 1.59 kg/capita/day, 130 tons per day which were contributed by 41 % from households and 59% from non-households as Thaklong is an urban commercial area. According to the analysis of waste composition from the households and waste collection trucks, organic waste is the largest portion, followed by plastic waste as the second, paper as the third while other wastes are not significantly too much and different. In overall MSW composition, similarly, organic waste is the largest portion about 64 % and plastic composition is the second largest about 18 %, followed by a paper third while other wastes are not significantly too much a lot of non-household premises such as markets contribute to high organic waste and plastic waste with the high plastic consumption. According to the WaCT assessment, in Thaklong, 83 % of MSW generated to enter the recovery system including the energy recovery and the material recovery by formal and informal sectors was relatively high to the disposal amount of 15 %. The total waste collection rate was 91 % owning to the large contribution of the MSW recovery amount while uncollected waste was 12 tons per day.

In Thaklong, plastic waste generation calculated by the WFD method was 8557 tons/year. Plastic waste was unmanaged at 926 tons/year about 11% of total plastic waste generation, which is a combination of uncollected plastic waste and plastic leakages from the solid waste management operations. The main contribution to unmanaged waste from uncollected waste was about 90.67 % and other leakages come 9.04 % from collection service, 0.01% from the informal value-chain collection, 0.14 % from formal sorting with no contribution from informal sorting and transportation. In the plastic pollution per fate, plastic waste was retained on the land about 55% equal to 511 tons/year, while some are either burned 120 tons/year about 13% and accumulates in drains 11 tons/year about 1%. The potential plastic leakage to waterways was estimated to be 31 % of unmanaged plastic waste equal to about 284 tons/year. Thaklong town releases 3.5 kg/capita/year of plastic waste to the water systems, which is equivalent to 116 PET plastic bottles released per person per year, 3 Olympic swimming pools per year, and 418 waste trucks with 20 m^3 per year estimated by the WFD excel based model.

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