DISPERSAL OF PLASTIC WASTE IN KHLONG U-TAPAO SUB-BASIN TOWARDS THE LOWER SONGKHLA LAKE, SOUTHERN THAILAND: A GIS-AHP APPROACH

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Abstract. Plastic waste that is not properly managed and leaks into the sea is becoming a serious problem of marine debris. The aim of this study is to analyze the distribution of plastic waste in the Khlong U-Tapao Sub-basin, which flows into the lower Songkhla Lake, Thailand, by using a geographic information system (GIS) and the Analytic Hierarchy Process (AHP), a multi-criteria decision analysis process (MCDA). Physical factors and different geographic environmental characteristics, for a total of 16 data layers representing the origin of plastic waste, rainfall, wind speed and wind direction, slope, past flood events areas, land use, distance from stream, the flow characteristics of the river and distance from the ocean, were collected from field survey and analyzed using GIS. The results showed that towns and cities are where most plastic waste leaks occurred. The majority of this waste enters the Khlong U-Tapao River. The rate of plastic waste leakage is higher during the monsoon and when there are floods. The output of this GIS-AHP method offers incredibly precise spatial data. This study effectively demonstrates how plastic waste from the land flows into the Khlong U-Tapao River and other streams that are connected to the lower Songkhla Lake. The findings can be used to develop guidelines for sustainable management of marine debris in the future.
Keywords: *marine debris, plastic leakage pathways, GIS-AHP integration, monsoon-induced dispersal, sustainable waste management*

Introduction

Currently, the issue of solid waste, particularly, which is sourced from land-based sources, including improper disposal of plastics, runoff from urban areas, and agricultural activities (Adetuyi et al., 2024; Leterme et al., 2023), stands as a pressing global environmental concern, reaching a critical juncture. A portion of this plastic waste remains inadequately managed, ultimately seeping into the ocean and exacerbating the issue of marine debris (Meijer et al., 2021; Neves et al., 2022; Sivadas et al., 2022). This marine debris poses significant threats to both the environment and the well-being of marine life, particularly due to the presence of toxins within small sized plastic debris known as "Microplastics" consisting of fragments measuring less than 5 mm (Arthur et al., 2009). The Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), defines microplastics as "plastic

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particles < 5 mm in diameter, which include particles in the nano-size range (1 nm)" (Andrady, 2017; Frias and Nash, 2019). Microplastics [MPs] have now become pervasive pollutants in our oceans, posing a grave menace to marine ecosystems. These plastic particles can accumulate in the bodies of marine organisms such as sea turtles, sea birds, shellfish, shrimp, and fish, as they are mistakenly ingested, and such accumulation of toxic residues can negatively affect health and growth. These plastic and toxic residues can pass to other organisms through the food chain and food web. Furthermore, there is a risk of these toxins accumulating in the bodies of humans who consume marine creatures that have been exposed to these pollutants (Chatterjee and Sharma, 2019). Thailand is grappling with escalating waste challenges, mirroring issues faced by numerous countries globally, particularly concerning plastic waste. Residual waste is a major concern for management of marine debris (World Bank, 2022). The accumulation of plastic waste in coastal areas predominantly results from inadequate waste management practices and the behavior of residents in these coastal regions (Taïbi et al., 2021). Thailand Plastic Waste Management Roadmap 2018-2030 has addressed the environmental pollution from plastic waste and the guidelines for management (Pollution Control Department, 2020), but this remains a serious issue. The primary source contributing 80% of plastic waste in Thai waters is the land-based and coastal activities of households and tourism. Dumping sites near shorelines release plastic bags, beverage lids, drinking straws, plastic cups, and food containers. The Pollution Control Department estimated that solid waste from 23 coastal provinces in Thailand was up to 11 million tons, of which 2.9 million tons was improperly disposed plastic waste. Among these, 343,000 tons is marine debris, and about 34,000 to 52,000 tons is found in 9 major river mouths in the upper and lower Gulf of Thailand. The largest quantity of floating garbage, averaging 52 million pieces per year (317 tons per year) flowed through the Chao Phraya River. In the lower Gulf of Thailand, the mouth of Songkhla Lagoon had the highest flow with an average of 5.5 million pieces per year (142 tons per year) (Department of Marine and Coastal Resources, 2022a, b).

Akkajit et al. (2021) examined the presence and distribution of microplastics in beach sediments along the coastline of Phuket province, a renowned tourist destination in Thailand. Their findings revealed the presence of microplastics such as polyethylene terephthalate, polyester, and polypropylene on six beaches situated on the east and west coasts of Phuket. The release of these microplastics was closely associated with beach tourism activities, especially with land-based sources at tourist departure points and port areas.

Songkhla Province faces a significant challenge in managing its waste disposal, which currently lacks a scientifically sound approach commensurate with the volume of waste generated. Consequently, a considerable amount of residual waste has accumulated in unscientific landfills throughout the province, totaling 23 locations spanning across its 16 districts. According to a report from Pollution Control Department (2018), Songkhla Province generated 760 tons of solid waste daily, with 668 tons being disposed of in a scientifically responsible manner and 92 tons were dumped improperly. From this, an alarming 23,000 tons of unmanaged residual waste has accumulated since 2014. This constitutes municipal solid waste that has not been appropriately handled. Regrettably, most of this waste is at risk of becoming marine pollution in vital waterways and canals within Songkhla Province, including Khlong Dan Canal, Khlong Ranot Canal, Khlong Takhriya Canal, Khlong Pak Ro, Khlong Pak Bang Phumi Canal, Bang Riang Canal, Bang Klam Canal, Khlong U-Tapao River,

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Chana Canal, and Nathawi Canal, as highlighted in reports by Environment and Pollution Control 16 (Songkhla) (2022) and Pollution Control Department (2018). Addressing these issues requires a comprehensive and scientifically informed waste management strategy to mitigate the environmental and health risks associated with the current state of waste disposal in Songkhla Province.

Geo-informatics technology consists of a suite of advanced tools, including Remote Sensing (RS), Geographic Information Systems (GIS), Global Positioning System (GPS), and Global Navigation Satellite System (GNSS). These technologies are currently used for creating geo-information resource databases, in order to monitor environmental changes spatially and temporally and for management of natural disasters and natural resources. GIS can be employed for cataloging agricultural plastic waste on land and generating informative maps. A distinctive feature of GIS is its ability to continuously update data, making it an invaluable tool for identifying regions with high concentrations of plastic waste. Furthermore, it can be used to suggest the optimal collection points on farms and streamline transportation routes to recycling facilities (Blanco et al., 2018; Jang et al., 2014; Morsink-Georgali et al., 2021). Remote sensing, especially through the utilization of high-resolution satellite imagery (Chen et al., 2021; González-Yebra et al., 2018; Lanorte et al., 2017) and high-resolution aerial imagery by drones (Deidun et al., 2018), has proven to be a highly effective method for surveying waste. Themistocleous et al. (2020) utilized high-resolution Sentinel-2 satellite imagery to investigate a floating raft of plastic waste near the old port of Limassol, Cyprus, and highlighted the effectiveness of near-infrared (NIR) wavelengths in detecting plastic waste. They introduced the innovative Plastic Index (PI) as the most efficient means of identifying surface-floating marine plastic waste. For decision-making and prioritization within this field, Multi-Criteria Decision Analysis (MCDA), particularly the Analytic Hierarchy Process (AHP) method developed by Saaty (1980) is a well-established and potent tool. Combining AHP with Geographic Information Systems (GIS-AHP modeling) facilitates complex decision-making processes. It finds utility in various applications related to resource and environmental management. The integration of remote sensing techniques and GIS tools with AHP is increasingly used for investigating plastic pollution (Ambrose et al., 2019; Blanco et al., 2018; Haarr et al., 2019; Loulad et al., 2017; Moy et al., 2018; Parlato et al., 2020; Rehn et al., 2018). The versatility and effectiveness of these methods in addressing contemporary environmental challenges needs to be assessed.

This study aims to analyze the spatial distribution of plastic waste within the Khlong U-Tapao Sub-basin using geo-informatics processes, including GIS and Remote Sensing. The research seeks to identify how land-based plastic waste is transported into the lower Songkhla Lake by examining key physical factors and environmental geographic characteristics.

Materials and methods

Study area

Khlong U-Tapao is a sub-basin nestled within the larger Songkhla Lake Basin (SLB), situated in the southern region of Thailand within the province of Songkhla. Spanning an expansive area of approximately 2,400 km^2, this region boasts the prominent Khlong U-Tapao River, a vital waterway stretching about 108 km, which holds the distinction of being the largest and most significant river in Songkhla Province. The Khlong U-

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Tapao River originates from the merging of several canals from the Khao Luk Chang and Banthat Mountain Range, located in Sadao District. It is also fed by a canal originating from Khao Nam Khang, near the Thai-Malaysian border. Flowing from south to north (Royal Thai Survey Department, 2000), the Khlong U-Tapao River ultimately terminates at the lower Songkhla Lake. Along its course, it traverses through several sizable urban communities, including Sadao City, Ban Phru City, Hat Yai City, and others. The Khlong U-Tapao River serves as a critical source of raw water for various purposes, including household activities, water supply production, fisheries, animal husbandry, agriculture, and industrial activities. It can collect solid waste generated by these activities, as well as wastewater from surrounding communities, prior to discharging into the outermost part of the lake that eventually connects to the Gulf of Thailand. The lower Songkhla Lagoon covers an area of approximately 182 km^2 with an average depth of approximately 1.5 m. This portion of the lagoon primarily consists of saltwater, although during the rainy season it can be brackish water due to the water runoff. This variability makes this region a crucial source for aquaculture activities. Additionally, the lower Songkhla Lake serves as a reservoir for solid waste within the broader SLB before it outflows into the Gulf of Thailand (*Fig. 1*).

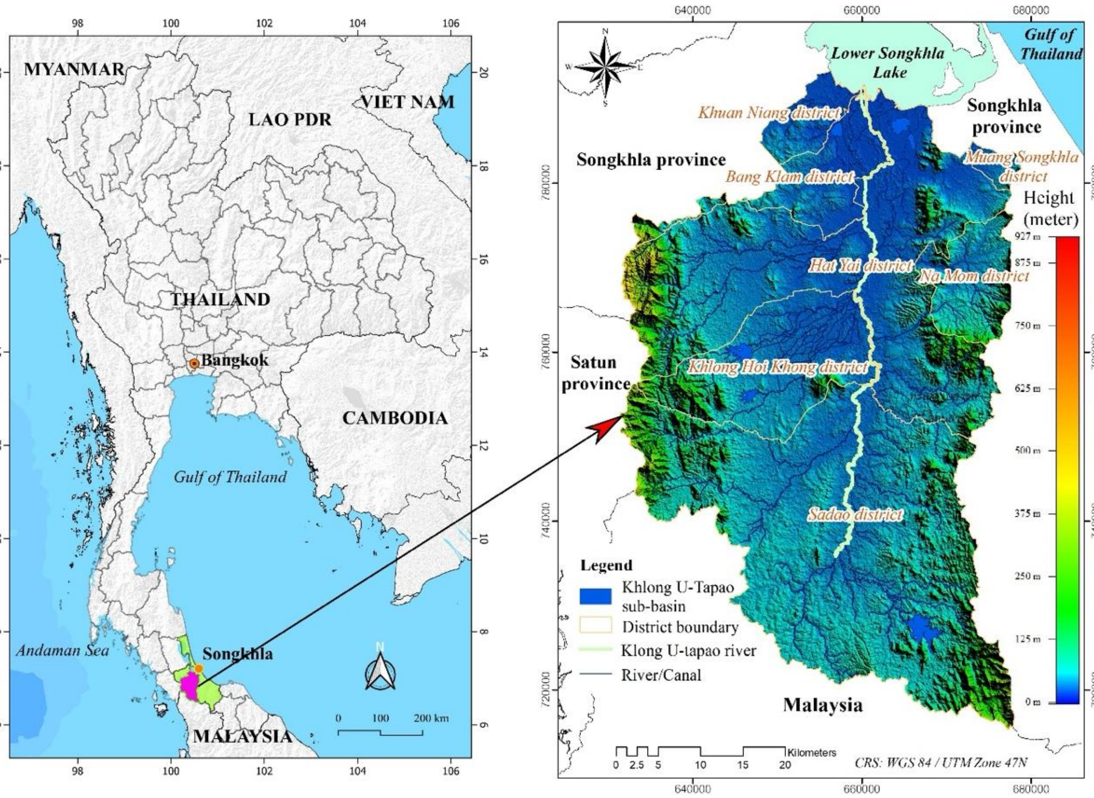

Figure 1. *Location of the study area along the Khlong U-Tapao Sub-basin*

Data collection

Data collection on sources and storage locations of waste, including waste disposal from landfills, households on land and waterways, agricultural activities, markets, and tourist attractions within the Khlong U-Tapao Sub-basin to the lower Songkhla Lake, was conducted between 2020 and 2022. Sentinel-2 (MSI) satellite imagery (spatial

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resolution: 10 × 10 m, source: https://dataspace.copernicus.eu/) was used to classify current land use through composite imaging and visual interpretation. High-resolution Google satellite images were employed to update information on land use, community locations, municipalities, and waterways. Rainfall patterns, wind speed, and wind direction data were collected over 10 years (2013–2022) from the Meteorological Department of Thailand, specific to Songkhla province. Physical and hydrological data for the study area were obtained from topographic maps provided by Royal Thai Survey Department (2000). Slope and elevation data were derived from the digital elevation model (DEM) of the study area. Fifteen spatial indicators likely to influence the movement of plastic waste from land to tributaries, and eventually to the lower Songkhla Lake via Khlong U-Tapao, were identified. These indicators were prioritized using the Analytical Hierarchy Process (AHP) based on their influence on plastic waste flow. After prioritization, GIS layers were created to facilitate spatial analysis of the Khlong U-Tapao Sub-basin. This analysis was conducted using QGIS software (QGIS Development Team, 2019) and involved overlaying multiple data layers, including administrative boundaries. A comprehensive map showing the distribution of plastic waste within the Khlong U-Tapao Sub-basin was also generated, highlighting areas where plastic waste is likely to leak into the lower Songkhla Lake.

Field surveys

Field surveys and data collection for the study area were conducted between 2021 and 2023 using two approaches:

Questionnaires: Data on the quantity of plastic waste from agricultural areas, as well as factors contributing to the distribution and leakage of plastic waste into water sources, were collected through surveys of 105 agricultural households located within 2 km of the main watercourse. Additionally, photographs and location coordinates (UTM) were recorded using GPS devices.

Drone-based Aerial Imaging: Orthophoto mapping was carried out using drones at nine connection points where watercourses flow into the lower Songkhla Lake, covering an area of approximately 100 × 100 m at each site. The captured images were processed into high-resolution orthophoto maps (resolution < 5 cm) to identify floating plastic waste on the water surface. These maps also served as a reference for verifying the accuracy of GIS-AHP data analysis.

Microplastics analysis

We used data of microplastic from Pradit et al. (2023). This study conducted surface water sampling four times in 2022, during February, April, June, and August, from seven different locations along the Khlong U-Tapao River covering upstream, midstream, and downstream areas.

Factors, indicators, and GIS layers for data acquisition

Key factors influencing the distribution of plastic waste within the Khlong U-Tapao Sub-basin to enter the lower Songkhla Lake were identified for creating comprehensive geographic information system data layers. These critical factors include: (1) origin and storage of plastic waste, (2) topographical and climatic conditions, and (3) distance factors. The identification of factors and criteria associated with these 16 data layers can create comprehensive GIS data layers. The details of these data layers are presented in *Table A1*.

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Analytic hierarchy process (AHP) analysis

The Analytic Hierarchy Process (AHP) (Saaty, 1980) and Multiple-Criteria Decision Analysis (MCDA) were used in this study. The hierarchical AHP analysis included the selection of relevant indicators, the determination of relative importances (AHP ranking), and data consistency assessment. Physical and environmental indicators pertinent to the distribution and leakage of plastic waste were identified. These indicators were evaluated by professionals who played integral roles in the focus group discussions, using questionnaires and interviews (*Table A1*). The order of importances (AHP Rank) was established by comparing these various factors systematically. This comparison took place through pair-wise assessments, creating a comparison matrix table, starting from the top level and descending to the bottom. Experts assigned importance ratings on a scale from 1 to 9, where 1 signified equal importances, and values greater than 1 indicated increasing order of importance, culminating in 9 for the most critical factors. Subsequently, the geometric means and weights were computed to derive a priority score. The data consistency assessment was done to ensure that the factor comparisons made in the study were reasonable and coherent. This involves calculating the Consistency Ratio (CR) using equations 1 and 2. A CR below 0.10 is considered acceptable. The equations for CR calculation are as follows:

$$\mathrm{CR} = \frac{CI}{RI} \qquad \text{(Eq.1)}$$

$$CI = \frac{\lambda\, max - n}{n-1} \qquad \text{(Eq.2)}$$

where CR is the consistency ratio, CI is the calculated proportion of consistency from equation (2), RI (Random Consistency Index) is a random consistency index obtained from a table, and n = number of factors of Saaty’s matrix (Saaty, 1980).

This rigorous AHP analysis allows us to methodically prioritize the factors related to plastic waste distribution and leakage, providing a sound foundation for informed decision-making in this context.

The AHP analysis results were utilized to determine the factors of highest priority within this study. The consensus among the majority of experts highlighted the significant impact of Distance factors on the spread and leakage of plastic waste within the Khlong U-Tapao Sub-basin, extending to the lower Songkhla Lake. Specifically, the distance of the river from the source of plastic waste within riverside communities, the distance from waste disposal sites and plastic waste landfills, the distance from plastic waste sources in agricultural areas, the distance from the stream to the waste collection route leading to the waste disposal pond, and the distance of the river from plastic waste sources in open market areas and tourist attractions, with AHP values of 0.1435, 0.1019, 0.0996, 0.0995, and 0.0939, respectively, were found to be the most influential factors. Following this, the type of land use and land cover was identified as another significant factor. In contrast, topographical and climatic factors exhibited relatively minimal influence, as indicated by the AHP values presented in *Table A1*. The obtained AHP predicted potential will be applied to rank the importance of the indicator factors. Subsequently, they will be multiplied by the criteria weights found in the table containing 15 predefined data layers within the GIS program. Each data layer is stored in the format of spatial data using the ESRI Shapefile format, preparing it for spatial data analysis in the upcoming steps. The

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resulting GIS-AHP are presented in *Table A1* and visualized as a map in *Figure 2*, in which λmax = 17.166, CI = 0.1547, RI = 1.59, and CR = 0.0972.

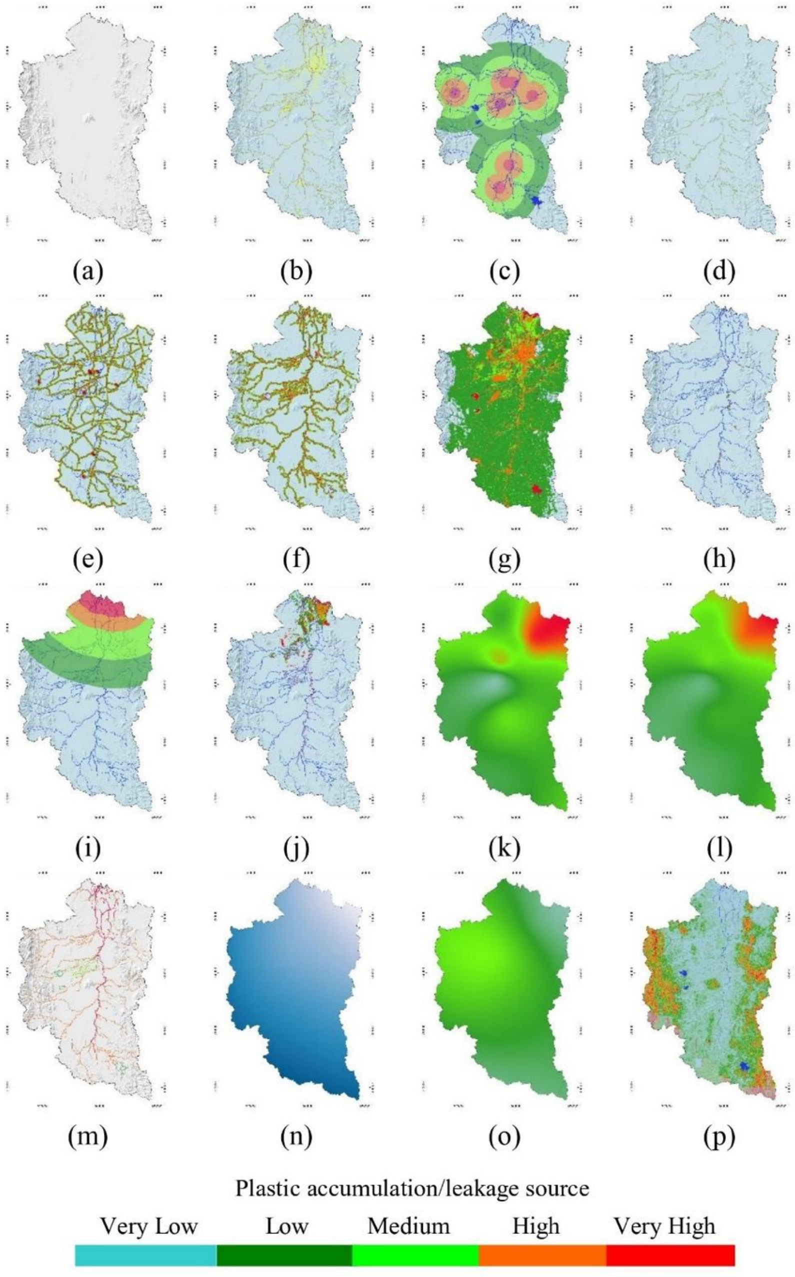

Figure 2. *The map data layers used in GIS overlay technique. (a) Khlong U-Tapao boundary, (b) distance between stream to point source of plastic waste from riverside community, (c) distance between stream to landfill open dumpsite, (d) distance between stream to point source of plastic waste from agricultural area, (e) distance between stream to point source of plastic waste from riverside route of garbage collection transport to landfill (road), (f) distance between stream to point source of plastic waste from market, open market area and tourist attraction, (g) land use and land cover, (h) distance between stream to point source of plastic waste from factory location, (i) distance between stream to the lower Songkhla Lake, (j) past flood events areas, (k) average annual rainfall (over 10 years), (l) average of annual rainfall of rainy season (October, November and December) over 10 years, (m) stream order, (n) average annual wind direction (over 10 years), (o) average annual wind speed (over 10 years), and (p) slope*

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Analysis of plastic waste pathways in the Khlong U-Tapao Sub-basin using GIS-AHP overlay

We employed the QGIS program to analyze the distribution path of plastic waste in the Khlong U-Tapao Sub-basin. This analysis utilized an approach often referred to as Multi-layer Overlay, and incorporated a model based on the work of Meijer et al. (2021) as expressed by *Equation 3* below.

The probability of plastic waste migrating from land into the sea, denoted by P(E), can be attributed to three primary factors:

$$P(E) = P(M) \times P(R) \times P(O) \quad \text{(Eq.3)}$$

Here P(E) represents plastic waste originating from land and eventually reaching the sea, P(M) refers to the mobilization of plastic waste on land, encompassing variables like precipitation, rainfall, and wind, P(R) pertains to the transport of plastic waste from land to rivers, considering factors such as terrain slope, land use, and proximity to rivers, and P(O) signifies the conveyance of plastic waste within rivers toward the ocean, accounting for river sequence (stream order), river discharge, and the distance from river or sea mouths to the ocean.

To perform the overlay analysis involving multiple data layers, derived from the aforementioned factors, we employ a method that calculates weighted average scores from the data layers. The weights reflect the significance of each indicator used in the computation, making it suitable for scenarios where not all information is of equal importance. This process is defined as follows:

$$P(E) = \sum_{i=1}^{n} c_i \times \lambda_i \, ; \sum \lambda_i = 1 \quad \text{(Eq.4)}$$

Here P(E) denotes plastic waste originating from land that will reach the sea, c_i represents the evaluation criteria for each factor utilized, λ_i stands for the weight associated with each evaluation criterion or factor i ($i = 1, \cdots, n$), and n indicates the total number of variables employed in the analysis.

Assessment of map accuracy

To assess the accuracy of the plastic waste route and leakage analysis, a map accuracy assessment was conducted by comparing the analysis results to reference data. The accuracy of the map was evaluated using a confusion matrix, which provides insights into overall accuracy, and Kappa statistic. This assessment employed an area selection approach, achieved through a simple random sampling of 30 points from the map generated in the preceding analysis. These points were overlaid with data collected during field surveys, as detailed in *Table 1*. The results of the map accuracy assessment revealed an overall accuracy of 60% and a Kappa statistic of 80%. These values indicate a high level of accuracy in the overall analysis.

QGIS software

QGIS (Quantum GIS) was employed for data importation, spatial analysis, and the creation of maps and tables in this study. QGIS is a widely recognized free and open-source Geographic Information System (GIS) software used for geospatial information processing (Moyroud and Portet, 2018; QGIS Development Team, 2019).

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Table 1. *General confusion matrix for accumulation/leakage source map*

Classification result	Plastics debris hotspot	Reference data			User's accuracy (%)
		Leakage hotspot	**Non-leakage hotspot**	**Total**	
	Leakage hotspot	11	4	15	73.3
	Non-leakage hotspot	2	13	15	86.7
	Total	13	17	30	
Producer's accuracy (%)		84.6	76.5		

Overall classification accuracy = 80%
Overall Kappa Statistic = 60%

Results and discussion

The distribution of plastic waste in the Khlong U-Tapao Sub-basin, which ultimately flows into the lower Songkhla Lake, was analyzed by the utilization of spatial data within the QGIS program. In conjunction with this software, we employed the AHP that integrates various physical factors and geographic environmental characteristics into a comprehensive analysis. In total, 16 layers of data were considered, making the AHP method a highly effective tool for prioritizing factors in decision analysis, as demonstrated in previous studies (Ajibade et al., 2019; Lella et al., 2017). Subsequently, the outcomes of this analysis were integrated with field survey data, supplemented by additional pertinent information such as topographic maps, land use data, very high-resolution satellite imagery, and ortho-aerial images obtained via unmanned aerial vehicles during the study period. This is consistent with the study of Meijer et al. (2021). Data on geographic factors, including topographic characteristics, land use, wind, rainfall, waterways, and information on the distance of garbage dumps and landfills from riverbanks, were collected. The data were then used to calculate the probability that plastic waste will reach rivers and later leak into the ocean. It was found that these factors contribute to the movement of plastic along with water flow. Moreover, more than 1,000 rivers, accounting for 80% of the world's rivers, release plastic into the ocean. Sakti et al. (2021) modeled the amount of plastic waste coming from the mainland that accumulates in river mouths, similar to the current study. This was achieved by gathering basic information on marine plastic management from the mainland, through the comprehensive context of data generated by remote sensing technology and geospatial analysis. The parameters used in this study cover plastic waste generation, ground cover, population distribution, and identification of human activities. These parameters were then used to create calculations based on weighting methods and overlapping analysis between land and coastal areas. Results indicate that 0.6% of Indonesia, including major cities, is considered the group that produces the most plastic.

Sources of plastic waste in the Khlong U-Tapao Sub-basin

Plastic waste within the Khlong U-Tapao Sub-basin originates from diverse sources, which can be categorized as follows.

Municipal solid waste from urban and municipal areas

This category encompasses solid waste generated from various activities within the local community, including residential areas, commercial establishments, business

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districts, retail shops, service centers, fresh markets, and various institutions. There are 20 cities in the Khlong U-Tapao Sub-basin, and the estimated population of this basin is about 692,000. Environment and Pollution Control 16 (Songkhla) (2022), the annual report on municipal solid waste (MSW) for 2022 from various communities in Songkhla province revealed that the total amount of waste generated within the Khlong U-Tapao Sub-basin was approximately 309,357 tons/year. The highest waste contributions came from municipalities within Hat Yai District, ranked as follows: Hat Yai Municipality 102,885.61 tons/year, Khuan Lang Municipality 21,010.59 tons/year, Kho Hong Municipality 19,320.67 tons/year, Khlong Hae Municipality 17,507.35 tons/year and Ban Phru Municipality 11,157.37 tons/year. Hat Yai Municipality reported 1,238 sources of solid waste, with the most significant contributors being, restaurants, hotels, resorts and dormitories, banks, government and private offices, markets, shopping malls, and educational institutions. The composition of the waste was as follows: food waste 48.15%, plastic waste 14.64%, glass 8.21%, paper 0.96%, and others 21.95%, This data aligns with the population density in these communities, as larger populations tend to generate higher amounts of solid waste.

Community waste disposal sites

Solid waste management in Songkhla Province has been driven by government policies emphasizing the clustering of local administrative organizations (LAOs) to manage waste collectively. This approach focuses on utilizing appropriate technologies based on the size of the cluster (small, medium, or large) and aligns with renewable energy policies. A key aspect of this strategy is the use of technologies to convert solid waste into energy (waste-to-energy), such as processing waste into refuse-derived fuel (RDF), biogas, heat, or electricity. Cluster formation is based on adjacent or nearby administrative areas, with the grouping determined by factors such as the volume of waste generated and the transportation distance required for waste collection. The waste transfer distance from LAOs to disposal sites should ideally be less than 40 km. Studies have shown that this distance is cost-effective for operations. Additionally, public acceptance within the area must be considered, as waste disposal activities can significantly impact both the community and the environment. There are a total of 8 community waste disposal sites in the sub-basin. Of these, 3 employ the sanitary landfill method for waste disposal, while 5 serve as factories that convert solid waste into electrical energy. Additionally, there is 1 facility dedicated to solid waste separation, producing Refuse-Derived Fuel (RDF), and 3 outdoor dumping sites.

Plastic waste from tourist attractions

Plastic waste in natural tourist attractions continues to be a persistent issue, despite campaigns urging tourists to take their waste with them. According to data from the Department of National Parks, Wildlife, and Plant Conservation (DNP) in 2021, plastic waste from tourist sites included: Plastic bags: 812,591 items, Single-use plastic cups: 208,179 items, Styrofoam food containers: 31,301 items. Additionally, single-use plastic straws have become a significant problem on tourist beaches. In response, the European Union imposed a ban on single-use plastic straws, which took effect in 2021 (Fanini and Guittard, 2021). Flea markets, community markets, and walking street markets are also major sources of waste. These markets often face insufficient waste bin

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availability to accommodate the large crowds. As a result, waste is frequently left on the ground, with some of it leaking into nearby waterways. Suburban flea markets typically cover larger areas than those in urban communities. However, waste collection in these areas is sometimes incomplete, leaving residual waste scattered across the site. This plastic waste is further dispersed by wind and rainwater runoff during the rainy season, exacerbating the problem. Various tourist attractions within the Khlong U-Tapao Sub-basin contribute to plastic waste generation. These attractions include flea markets, walking street markets, open-air markets, floating markets, public parks, temples, waterfalls, and more. In total, there are 97 such locations in the sub-basin.

Plastic waste from communities along the river

Rivers, in addition to serving as transportation routes and supporting agricultural activities, are often home to communities that settle along their banks. Some areas are also significant tourist attractions. These locations are often major sources of waste situated close to water bodies. The issue of floating waste accumulating in canals is commonly observed, caused by several factors. These include careless disposal of waste directly into rivers and canals by residents, as well as spatial limitations in certain communities, such as narrow alleys that make it inconvenient for residents to transport their waste to designated disposal points. As a result, improper waste management often leads to residual plastic waste within these communities, most of which consists of single-use plastics (Cordova et al., 2024). During the rainy season, rainwater washes larger quantities of waste into canals than usual. Ultimately, a significant amount of human-generated waste can be transported downstream to river mouths and eventually into the ocean (Moss et al., 2021; Rech et al., 2014). This category includes plastic waste originating from both urban and riverside communities. Notable communities contributing to plastic waste in this category include Sadao Community, Khuan Lang Community, Hat Yai Community, and Khlong Hae Community.

Plastic waste from agricultural areas

Plastic plays a significant role in agriculture, contributing to increased productivity and improved quality of agricultural outputs. As a result, plastic has become indispensable in the agricultural sector. It is widely used for purposes such as crop protection, shading, mulching, irrigation, silage wrap, harvesting, post-harvest processing, seedling pots, trays, containers, packaging, and sacks. While the use of plastics in agriculture offers many benefits, it also leads to the generation of significant amounts of waste (Hachem et al., 2024; Lanorte et al., 2017; Qadeer et al., 2021; Zhao et al., 2024). In the study area, plastic waste from agricultural activities was assessed using the 2022 land-use map of the Khlong U-Tapao Sub-basin, along with field surveys, interviews, and questionnaires with local farmers. These included rubber plantation workers, oil palm growers, and fruit orchard owners. The findings indicated that the use of plastic mulch is common in vegetable and fruit plantations, while plastic nursery bags are often discarded near water sources. This plastic waste is frequently transported into nearby canals, driven by strong winds during monsoon seasons or carried by water during floods and overflows. The waste eventually collects in natural streams before flowing into the main canals. Agricultural areas cover a substantial portion of the Khlong U-Tapao Sub-basin, spanning approximately 1,770 km^2. Within these areas, plastic waste generation is a significant concern.

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Plastic waste from fisheries and aquaculture

Plastic waste entering the ocean primarily originates from land-based sources, leading to significant attention on single-use plastic packaging. However, plastic waste from fishing activities also contributes substantially to marine pollution (Apete et al., 2024; Pinheiro et al., 2021). Field surveys conducted in the study area revealed that most of the plastic waste in this category is concentrated at the mouths of canals that flow into Lower Songkhla Lake. Typical items found in this waste stream include plastic fishing nets, rope fragments, and plastic materials used for boat coverings.

These multiple sources collectively contribute to the plastic waste problem in the Khlong U-Tapao Sub-basin, necessitating comprehensive strategies for waste management and pollution control. It is necessary to have a thorough waste management and pollution control strategy. This is consistent with the study by Meijer et al. (2021). Plastic pollution in waterways and oceans is increasing rapidly these days. Approximately 60% of all plastics often come from being discarded in landfills or in the natural environment. At the same time, the use of plastic mulch materials in agricultural areas is increasing, especially in developing countries. Agricultural plastic mulching is used to maintain temperature, soil moisture, and plant transpiration rate, and to increase crop production. Plastic mulching is considered an important source of microplastics (MPW) in terrestrial ecosystems because it is widely used. If there is a lack of proper plastic waste disposal and improper management, plastic mulch fragments can also travel through rivers, streams, and eventually into the ocean (Qadeer et al., 2021).

In addition to releasing plastic into the ocean each year, the majority of plastic waste (98.5%) remains in the terrestrial environment where it accumulates and persists, polluting terrestrial and aquatic ecosystems. This is because most of the MPW is generated and remains in the soil. Therefore, prevention and mitigation of impacts by reducing waste, collecting and properly disposing of waste on land, as well as cleaning, will have the biggest impact on reducing the release of plastic into the ocean.

The route of plastic waste from land sources in the Khlong U-Tapao Sub-basin to flow into the lower Songkhla Lake

Through the analysis of spatial data, we were able to map the travel route of plastic waste in the Khlong U-Tapao Sub-basin to the lower Songkhla Lake. It was discovered that within the Khlong U-Tapao Sub-basin, there are approximately 2,000 streams, comprising 1,576 small and large reservoirs, with streams that maintain a consistent flow throughout the year. There are 304 rivers, and most of these rivers are interconnected. Most of these waterways converge at the Khlong U-Tapao River, making it the primary route for transporting plastic waste to the lower Songkhla Lake before it enters the Gulf of Thailand (see *Fig. 3*). The Khlong U-Tapao River is the longest natural mainstream in the basin, spanning a total length of 108 km, with a river width ranging from approximately 2 to 250 m. The Khlong U-Tapao River consistently carries water throughout the year, flowing from the south to the northern mouth of the canal before discharging into the lower Songkhla Lake. The Khlong U-Tapao River traverses many large urban communities, including the Sadao community, Khuan Lang community, Hat Yai Community, and Khlong Hae Community, before reaching the lower Songkhla Lake. The journey of plastic waste in the Khlong U-Tapao River primarily originates from riverside communities. Plastic waste is often disposed of

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directly by dumping and is subsequently washed away by the water. Most of the plastic waste consists of plastic bags, plastic bottles, and foam food boxes. There is also vinyl plastic waste, which includes small pieces of advertising signs, and some plastic waste comes from agricultural areas on both sides of the Khlong U-Tapao River, including plastic bags containing rubber seedlings, palm oil, and various fruit trees. Farmers typically discard these plastic bags, and small black plastic leaflets are often placed in the holes where the seedlings are planted. If these waste items are within 10-15 m of the river, they are frequently washed into tributaries and carried into the Khlong U-Tapao River during the rainy season or monsoon periods. This occurs because there are often floods that inundate the canals during heavy rain, or continuous rainfall spanning several days. The prevailing monsoon winds play a vital role in defining the route and the destination of floating debris. Large quantities of plastic waste are released into the sea (Iskandar et al., 2022), potentially exacerbated by flooding issues. These wastes tend to be swiftly carried away by the water. Most plastic waste is carried away by the numerous rivers that flow through densely populated urban areas, rather than originating from a single large river. Therefore, microplastics (MPW) near rivers and close to the coast have a higher probability of entering the ocean, while MPW farther upstream in a basin has a lower probability of entering the ocean (Meijer et al., 2021). Thailand generates approximately 12% of its total waste as plastic waste (Office of Natural Resources and Environmental Policy and Planning, 2022). In 2022, the total municipal waste generated in 44 municipalities within the study area amounted to 309,357 tons per year (Environment and Pollution Control 16 (Songkhla), 2022). Of this, about 37,123 tons per year is plastic waste. Additionally, plastic waste from agricultural activities in the study area was found to include HD, HDPE, or PE plastic bags used for propagating seedlings in rubber plantations, oil palm plantations, fruit tree orchards, and tree nurseries. Mulching films made of PE plastic and woven plastic sheets (PP, PE, HDPE) used in vegetable fields were also identified. Therefore, the study area generates approximately 66 tons of plastic waste from agricultural activities per year. The Marine and Coastal Resources Research Center (Lower Gulf of Thailand) (2022) conducted a survey to identify and quantify solid waste collected using marine litter traps at key canals and river mouths in Songkhla Province. The survey spanned four months (July to October), representing both dry and wet seasons of 2020. Waste was collected and sorted following the International Coastal Cleanup (ICC) methodology. Across Songkhla Province, a total of 32,700 waste items were recorded, weighing approximately 6,562 kg. The most common waste types were food packaging, plastic bags (carry bags), and rubber bands. Coastal activities and recreational use were identified as the primary sources of waste. During the wet season, significantly more waste was observed compared to the dry season, with the highest waste accumulation recorded at the Songkhla Lake estuary. At Bang Klam River, a total of 2,193 waste items were collected using litter traps, weighing approximately 349.20 kg. October recorded the highest waste accumulation, with 1,192 items, the most common being single-use plastics (224 items). This canal runs through communities, tourist areas, and agricultural lands, which contributes to a large amount of plastic bag waste. At Khlong U-Tapao River, a total of 877 waste items were collected, weighing approximately 233.10 kg. October also saw the highest waste accumulation, with 37 items, the most common being glass beverage bottles (58 items). These bottles were primarily energy drink containers, likely discarded by agricultural workers from the medium and large-scale farms located along both sides of the canal.

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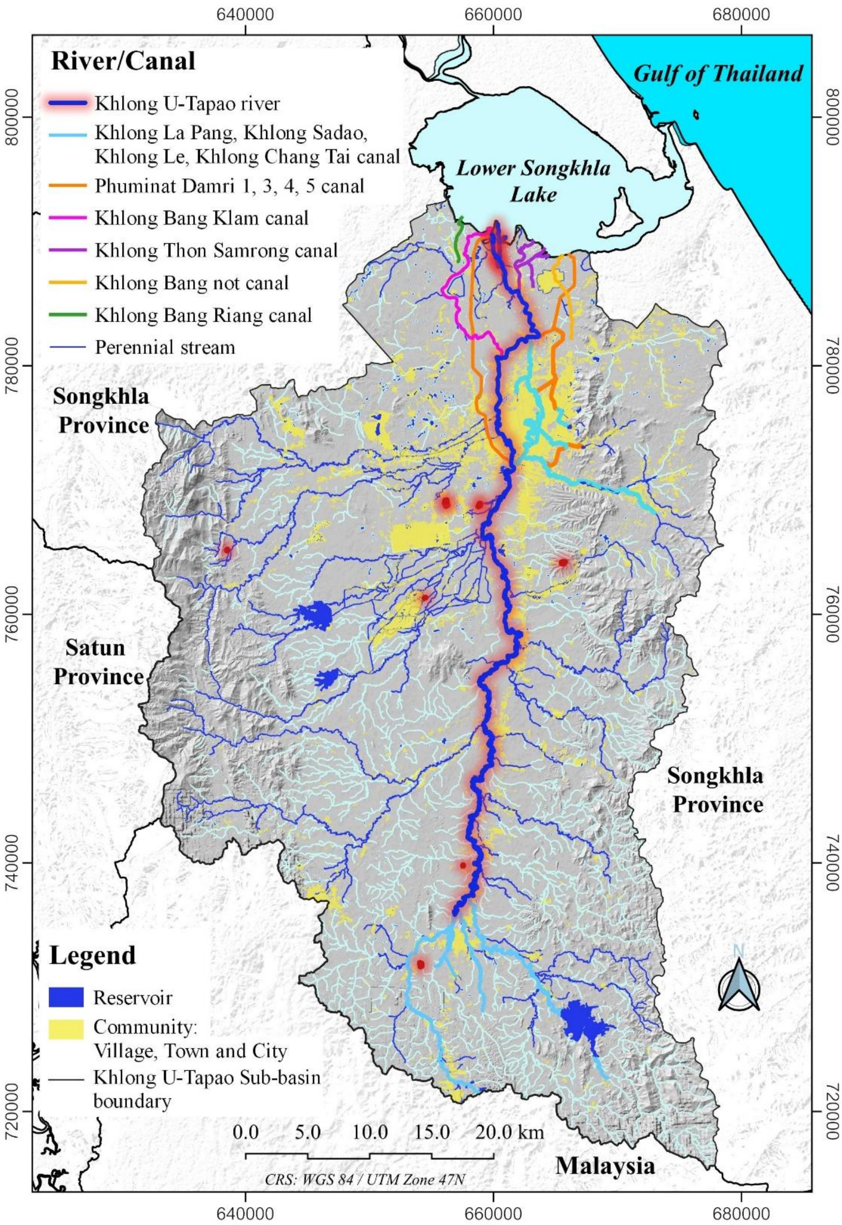

Figure 3. *The waterways that can carry plastic waste and flow into the lower Songkhla Lake*

This map was created by analyzing spatial data using the GIS program. Sixteen layers of data, obtained through the AHP hierarchical analysis method, were overlaid to assess factors related to the distribution of plastic waste on land that might be transported into the lower Songkhla Lake. A total of 15 factors were considered to determine the probability of plastic waste from land leaking into the waterways of the Khlong U-Tapao Sub-basin before flowing into the lower Songkhla Lake. The resulting map displays spatial information regarding areas expected to be potential points of accumulation and leakage of plastic waste into various streams within this basin. The opportunity (Class) was divided into five levels using the Natural Breaks (Jenks) method, with points of highest accumulation and leakage shown in red, indicating very high potential. Following that, orange represents high potential, green indicates medium potential, while dark green and light blue signify very low and low potential, respectively. The spatial data analysis

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revealed 51 points of accumulation and leakage of plastic waste into various streams within the Khlong U-Tapao Sub-basin before they reach the mouths of various canals leading to Lower Songkhla Lake. These points are shown on the map in *Figure 4*. The highest accumulation and severity of plastic waste leakage typically occur in the primary waterway of the Khlong U-Tapao Sub-basin, namely the Khlong U-Tapao River, or canals connected to it (*Fig. 5*). Plastic waste accumulation and leakage are notably concentrated in urban areas, which serve as significant sources of plastic waste. Consequently, plastic waste leakage is more pronounced in urban areas, as indicated on the map. When the Khlong U-Tapao River passes through densely populated urban communities such as Sadao, Khuan Lang, Hat Yai, Kho Hong, and Khlong Hae, there is a high potential for concentrated plastic waste accumulation and leakage (red). Moreover, areas of plastic waste accumulation and leakage often coincide with tourist attractions, such as floating markets and flea markets (*Fig. 6*). These issues are most pronounced in the heart of the city, where human activities contribute significantly to plastic waste generation. This increased waste production leads to a higher likelihood of plastic waste leakage. Plastic waste from urban areas can enter rivers more easily than from forest areas (Meijer et al., 2021) (*Fig. 7*).

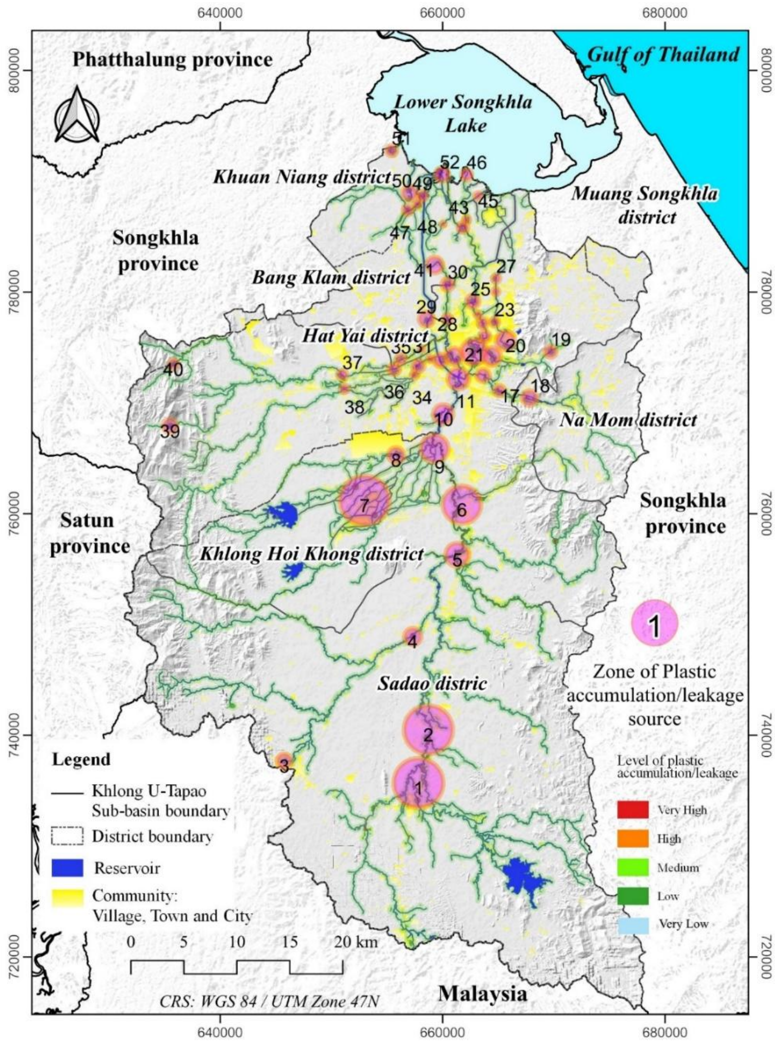

Figure 4. *Map of accumulation/leakage sources of plastic waste relevant to waterways in the Khlong U-Tapao Sub-basin by GIS-AHP analysis*

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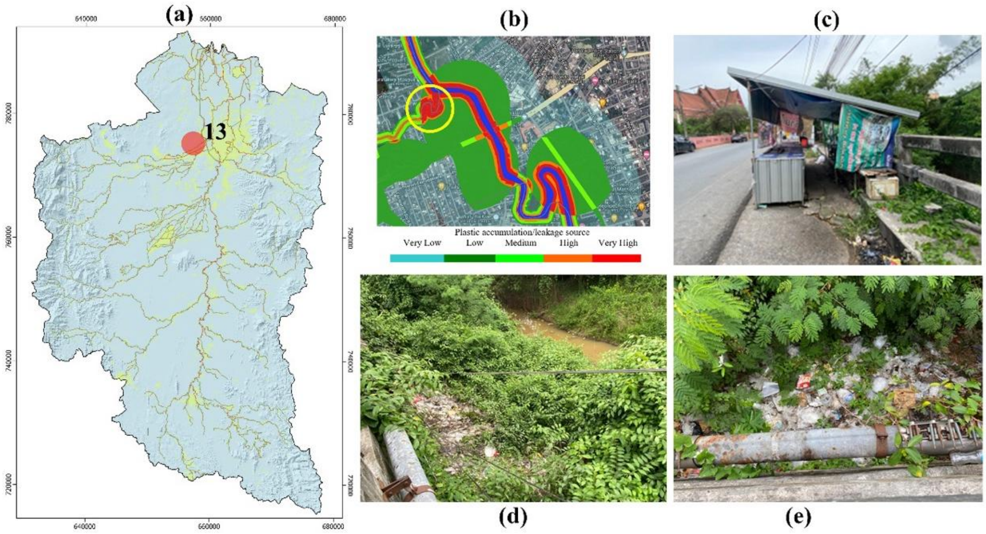

Figure 5. *(a) A map showing areas where plastic waste accumulates/leaks in the Khlong U-Tapao Sub-basin, zone 13. (b) Areas of very high levels of plastic waste accumulation/leakage obtained from spatial analysis in the low-lying canal area (in yellow circle) connecting to the Khlong U-Tapao River. (c, d, e) Photos of plastic waste along the Khlong U-Tapao River from surveys in the actual area*

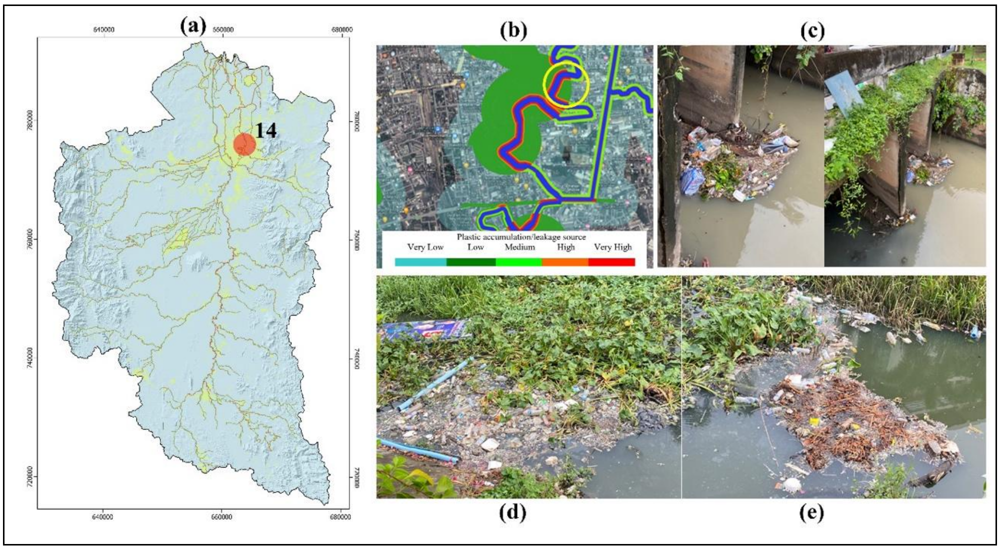

Figure 6. *(a) A map showing areas of accumulation/leakage of plastic waste in the Khlong U-Tapao Sub-basin, zone 14. (b) Areas of accumulation/leakage of very high levels of plastic waste obtained from spatial analysis in the Kong Khong open market area in the yellow circle. It is next to the Khlong Toei Canal in Hat Yai City Municipality. (c, d, e) Photos from the area where the open market is located. Plastic waste often leaks into the Khlong Toei Canal before flowing out into the Khlong U-Tapao River*

The map depicts areas of plastic waste accumulation and leakage on land before it enters the waterways within the Khlong U-Tapao Sub-basin

While urban areas exhibit high levels of plastic accumulation and leakage into the Khlong U-Tapao River, some communities with proper waste collection and

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management systems manage to reduce plastic waste (Hendrawan et al., 2023; Wichai-utcha and Chavalparit, 2019). Many municipalities are actively implementing measures to minimize plastic waste leakage in urban areas. In contrast, areas outside urban regions, including tourist attractions like Khlong Hae Floating Market and Ban Phru Floating Market near the Khlong U-Tapao River, also have a high potential for concentrated plastic waste accumulation and leakage. According to a study by Meijer et al. (2021), waste dumping sites and landfills within 10 km of the river can contaminate the river. As for garbage disposal sites (outdoor dumping) and the three plastic waste landfills within the study area, these are significant sources of plastic waste accumulation. However, their distance from main water sources generally limits their influence on plastic waste leakage, but in some years, there are natural disasters caused by strong winds (windstorms). There is a chance that small and light pieces of plastic waste can float away and fall into nearby tributaries during the rainy season with flash floods, and plastic waste can then move farther than in other seasons. A World Bank field study (World Bank, 2022) concluded that MPW leaks from individual rivers during the wet season may be twice the amount released during the dry season.

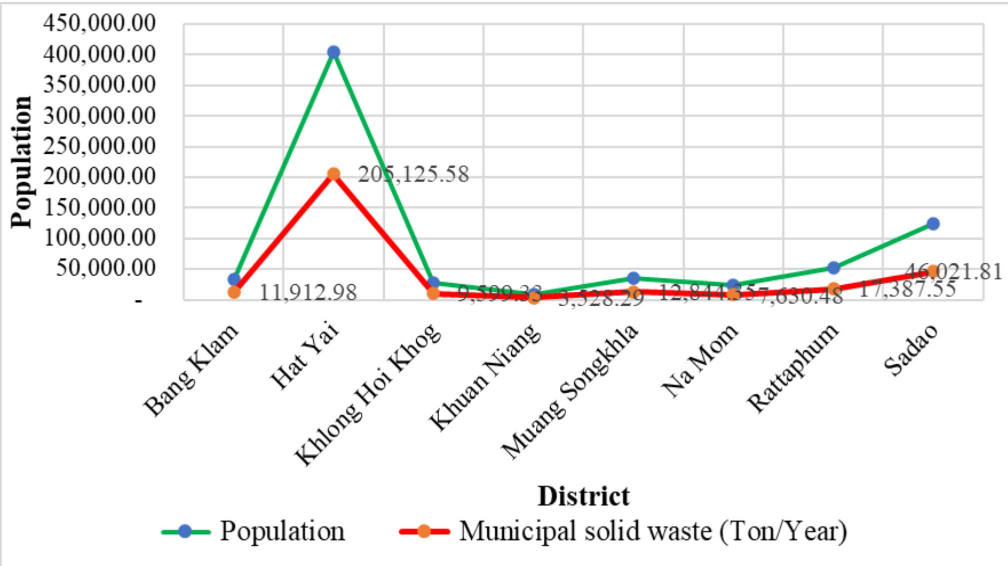

Figure 7. *Population counts of dense urban communities that produce the most solid waste, thus becoming large sources of plastic waste*

Several factors contribute to the release of residual plastic waste into the environment, with wind-related leaks being one of them. Wind can easily transport lightweight waste, especially plastic, which facilitates its spread and environmental contamination (de Oliveira et al., 2024; Meijer et al., 2021). Flood-related leaks are another concern. During floods, solid waste can be distributed and transported to water bodies, worsening the pollution problem (Rech et al., 2014; Yadav et al., 2020). Waste spills along the route can also be caused by transportation, animals, and human beings, leading to additional environmental pollution. Improperly disposed waste which can be reached by animals, and illegal dumping and littering by people, can contribute to plastic waste reaching water bodies and flowing into the sea (Ryan and Perold, 2021; Yadav et al., 2020). Each type of plastic takes at least 10 years to decompose, so it can

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contaminate water for an extended period. Marine animals can easily consume microplastics that are broken into small pieces. Data from Pradit et al. (2023) found that microplastic (MP) contamination was found in the U-Tapao Khlong River from upstream to downstream. Microplastic fibers were the most abundant type, accounting for more than 80% of the total in the Khlong U-Tapao River. The concentrations of microplastic during February, April, June, and August were 0.41 ± 0.08, 0.25 ± 0.06, 0.24 ± 0.11, and 0.26 ± 0.06 particles per liter, respectively. Jitkaew et al. (2023) investigated the amount of microplastics in river shrimp in the Khlong U-Tapao River. Fibers were the most prevalent type of microplastics in white shrimp (*Metapenaeus moyebi*), while fragments were the most prevalent type in *Macrobrachium rosenbergii*. Most of the microplastics found in *M. moyebi* were less than 100 µm in size, while those in *M. rosenbergii* were larger than 1 mm. This study also identified a variety of colors for microplastics, including blue, black, dark blue, red, and green. Microplastic contamination in these aquatic animals is concerning, as it can be transferred through the food chain to potentially affect humans.

Conclusions

This study demonstrated an effective method for assessing the accumulation and leakage of plastic waste from point sources into waterways at the basin level. By using layers of spatial data from multiple sources, in combination with overlay methods in the GIS, AHP was utilized as a multi-criteria data management and analysis tool to support effective spatial decision-making. Because it is structured to mimic human thinking processes, the use of GIS-AHP helps determine the importance of selected criteria and aids in assigning weights to each factor based on expert opinion. It can display information in the form of maps and tables, effectively representing the spatial situation in the study area. This allows for a better understanding of how plastic waste from the land flows into the waterways connected to lower Songkhla Lake, particularly focusing on the spatial distribution of plastic waste. Our analysis reveals the detailed spatial distribution of plastic waste within the Khlong U-Tapao Sub-basin, identifying key areas of concern and areas requiring further investigation and monitoring. In a comprehensive environmental assessment, through the integration of multiple layers of data and the application of AHP methods, we not only determine the distribution of plastic waste but also assess key physical factors and environmental characteristics contributing to this problem. This holistic approach provides valuable insights for decision-makers in prioritizing actions to address local plastic waste pollution. This approach can be customized for specific area-based applications, preventing plastic waste from seeping into the sea, and ultimately mitigating plastic pollution. Such measures are crucial in preventing microplastics from affecting the marine ecosystem and play a vital role in maintaining the health of the marine environment, which serves as a food source for humans.

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APPENDIX

Table A1. *AHP rating, indicators, and AHP predicted potential of indicators in the GIS layers*

AHP rating	Indicators/criteria in the GIS layers	AHP predicted potential	GIS method and data sources
1 (0.1435)	Distance from stream to point source of plastic waste from riverside community 1) >40 m 2) 30-40 m 3) 20-30 m 4) 10-20 m 5) <10 m	Very low Low Medium High Very high	Ground survey and interpretation from Google satellite images 2020-2022, Polygon, Buffering distance by GIS
2 (0.1019)	Distance from stream to landfill open dumpsite 1) >14 km 2) 9-14 km 3) 5-9 km 4) 2-5 km 5) <2 km	Very low Low Medium High Very high	Landfill open dumpsite location capture form UAV and Google Satellite 2020-2022, Polygon, digitize by GIS
3 (0.0996)	Distance from stream to point source of plastic waste from agricultural area 1) >50 m 2) 30-50 m 3) 20-30 m 4) 10-20 m 5) <10 m	Very low Low Medium High Very high	Land use map, Ground survey and questionnaire from farmer, Polygon, LULC Classification by GIS
4 (0.0995)	Distance from stream to point source of plastic waste from riverside route of garbage collection transport to landfill (road) 1) >300 m 2) 200-300 m 3) 100-200 m 4) 50-100 m 5) <50 m	Very low Low Medium High Very high	Ground survey and interpretation from Google satellite images 2020-2022, Polygon, Buffering distance by GIS
5 (0.0939)	Distance from stream to point source of plastic waste from market, open market area and tourist attraction 1) >500 m 2) 300-500 m 3) 200-300 m 4) 100-200 m 5) <100 m	Very low Low Medium High Very high	GEO-Informatics Center, PSU, Ground survey, Point/Polygon, Euclidean Allocation distance by GIS
6 (0.0643)	Land use and land cover 1) Forest land 2) Rangeland 3) Agricultural land 4) Urban and Built-up land 5) Bare soil, Roads 6) Water Body	Very low Low Medium High Very high Very high	Land use map 2018 of Land Development Department, and update with Google satellite images 2020-2022, Polygon, LULC classification by GIS
7 (0.0608)	Distance from stream to point source of plastic waste from factory location 1) >500 m 2) 300-500 m 3) 200-300 m 4) 100-200 m 5) <100 m	Very low Low Medium High Very high	GEO-Informatics Center, PSU, Ground survey, Point/Polygon, Euclidean Allocation distance by GIS
8 (0.0512)	Distance from stream to the lower Songkhla Lake 1) >30 km 2) 20-30 km 3) 10-20 km 4) 5-10 km 5) 0-5 km	Very low Low Medium High Very high	GEO-Informatics Center, PSU, Polygon, Buffering distance by GIS
9 (0.0491)	Past flood event area 1) Never flooded 2) Flooded 1 yrs 3) Flooded 2 yrs 4) Flooded 3 yrs 5) Flooded 4 yrs	Very low Low Medium High Very high	Past flood events areas 2017-2020 (GISTDA. https://flood.gistda.or.th/) Polygon, Shape ESRI, Flood classification by GIS
10	Average annual rainfall over 10 years		Total annual precipitation 2013-

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AHP rating	Indicators/criteria in the GIS layers	AHP predicted potential	GIS method and data sources
(0.0489)	1) <500 mm 2) 501-1,000 mm 3) 1,001-1,500 mm 4) 1,501-2,000 mm 5) >2,000 mm	Very low Low Medium High Very high	2022 of Songkhla province, Meteorological Department of Thailand, Polygon/Raster, Isohyetal map by GIS Interpolation
11 (0.0441)	Average annual rainfall in rainy season (October, November and December) over 10 years 1) <1000 mm 2) 1001-2001 mm 3) 2001-3001 mm 4) 3001-4000 mm 5) >4000 mm	Very Low Low Medium High Very high	Total annual precipitation 2013-2022 of Songkhla province, Meteorological Department of Thailand, Polygon/Raster, Isohyetal map by GIS Interpolation
12 (0.0429)	Stream order 1) Stream order 5 2) Stream order 4 3) Stream order 3 4) Stream order 2 5) Stream order 1	Very low Low Medium High Very high	GEO-Informatics Center, PSU and Google satellite images 2020-2022, Vector, Polygon, Buffering distance by GIS
13 (0.0363)	Average annual wind direction over 10 years 1) S, ESE, SE, SSE, SSW, SW, WSW, E, W 2) ENE, WNW 3) NE, NW 4) NNE 5) NNW 6) N	Very low Low Medium High High Very high	Total annual of wind speed 2013-2022 in Songkhla province, Meteorological Department of Thailand, Polygon/Raster, Wind direct map by GIS Interpolation
14 (0.0349)	Average annual wind speed over 10 years (miles per hour) 1) < 13 mph 2) 13-18 mph 3) 19-24 mph 4) 25-31 mph 5) 32-38 mph 6) >39 mph	Very low Low Medium High Very high Very high	Total annual of wind speed 2013-2022 in Songkhla province, Meteorological Department of Thailand, Polygon/Raster, Wind speed map by GIS Interpolation
15 (0.0291)	Slope (%) 1) < 5% (<2.8624 Degree) 2) 5-25% (2.8624 - 14.0362 Degree) 3) 25-35% (14.0362 - 19.2901 Degree) 4) 35-60% (19.2901 - 30.9637 Degree) 5) <60% (>30.9637 Degree)	Very low Low Medium High Very high	Raster DEM 1:4,000 (2002), Land Development Department, NASA SRTM Digital Elevation 30 m. (Area of Thailand-Malaysia border), Raster, Slope classification by GIS

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