Spatial and Temporal Patterns of Riverine Plastic Waste Inputs to the Ocean in Sri Lanka: Integrating Waste Management Archetypes and Hydrological Drivers

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Abstract*— Understanding the plastic waste input to the ocean is a critical study to keep the Indian ocean clean, The research problem addressed in this study is to quantify, analyze, and visualize the spatial and temporal patterns of plastic waste inputs from river mouths into the ocean in Sri Lanka. This involves integrating geospatial and tabular data on riverine plastic pollution, identifying high-contributing river mouths, examining seasonal trends, and relating these patterns to waste management archetypes. The ultimate goal is to inform targeted interventions for reducing plastic leakage from land-based sources into marine environments. This research would analyze the spatial distribution and seasonal trends of plastic waste entering the ocean from Sri Lankan rivers, using geospatial and statistical methods. It would also examine how different waste management archetypes contribute to plastic leakage, and assess the influence of hydrological variables (e.g., runoff) on plastic input variability. The findings could inform targeted interventions for reducing plastic pollution at critical river mouths and improving waste management strategies. The research integrates Geographic Information Systems (GIS), remote sensing data, hydrological analysis, and field sampling to identify high-risk zones. We have employed Getis-Ord Gi* and Kernel Density Estimation (KDE) to identify statistically significant clusters. The primary results show strong correlations between plastic accumulation and anthropogenic activities including urban runoff, tourism, and inadequate waste management. The findings provide an evidence-based framework for targeted interventions and sustainable policy development.

***Keywords*—** *Spatial hotspot modelling, Computational modeling, Plastic pollution , Waste management*

I. Introduction

Freshwater ecosystems play a vital role in sustaining biodiversity, supplying drinking water, and supporting socio-economic activities. However, plastic pollution from both point sources—specific, identifiable locations like wastewater outlets, industrial discharge pipes, or waste dumping sites. Further, non-point sources—more diffuse and difficult to track, like runoff from urban streets, agricultural fields, and stormwater flows is posing an increasing threat to these systems. This makes prevention and control more difficult because pollution can enter the system from both widely dispersed pathways and clearly defined locations. Sri Lanka's lakes, which are crucial for irrigation, fisheries, and tourism, are experiencing a rising influx of plastic debris due to rapid urbanization and ineffective waste management practices. While marine plastic research has gained significant attention, limited work has focused on inland water bodies. Plastic pollution in freshwater ecosystems has emerged as a critical environmental issue, impacting biodiversity, water quality, and human health [1]–[3]. Recent studies in Sri Lankan lakes show significant microplastic contamination in water, sediments, and macrophytes, highlighting the urgent need for monitoring and mitigation [1], [2]. To address this, this study proposes a spatial hotspot modeling approach to assess and predict plastic leakage patterns, allowing identification of high-risk areas and supporting targeted interventions [3].

Waste management is the process of gathering, moving, processing, recycling, and getting rid of waste products in a way that has the least negative effects on the environment and human health. Reducing waste production at its source, encouraging recycling and reuse, and making sure that any leftover materials are safely disposed of in landfills or burned are all components of effective waste management. It deals with a variety of waste types, such as hazardous materials, electronic waste, industrial waste, and municipal solid waste. In order to encourage sustainability, contemporary waste management systems also integrate community involvement, technology, and policies. Effective management promotes environmental and public health protection, lowers pollution, and conserves resources. The buildup of plastic products and particles in the environment that negatively impacts wildlife, ecosystems, and human health is referred to as plastic pollution. Plastics are persistent in rivers, oceans, and terrestrial environments because of their slow degradation and durability. They frequently decompose into microplastics that enter food chains. Urban runoff, improper disposal, industrial waste, and single-use plastics are some of the sources. In addition to contaminating soil and water and contributing to chemical leaching, plastic pollution disturbs aquatic life. In order to address this issue and lessen its effects on the environment and society, integrated strategies are needed, such as lowering the production of plastic, enhancing waste management, encouraging recycling, and increasing public awareness.

Spatial hotspot modelling is a technique for locating and assessing regions with noticeably high or low concentrations of a specific phenomenon is spatial hotspot modeling. Analysts can ascertain whether clustering patterns are random or significant by using statistical methods like Getis-Ord Gi*, Moran's I, or spatial scan statistics. This approach is frequently used to identify problem areas and distribute resources efficiently in the fields of environmental science, public health, criminology, and urban planning. By identifying critical areas, such as hotspots for plastic pollution in lakes or areas where air quality is deteriorating, it allows for targeted interventions in environmental applications, directing mitigation, policy, and monitoring efforts. Moreover, the process of representing, analyzing, and forecasting real-world systems or phenomena through the use of computer-based algorithms, simulations, and mathematical models is known as computational modeling. It enables scientists to test out intricate situations that might be too expensive, risky, or impractical to investigate in person. Simple deterministic equations to sophisticated agent-based simulations and machine learning systems are examples of these models. Computational modeling is used in environmental science to simulate pollutant dispersion, predict the effects of climate change, and evaluate ecosystem responses. It facilitates scenario testing, decision support, and enhanced comprehension of processes in the scientific, engineering, and social domains by combining data, theories, and computing power.

KDE is a spatial interpolation and visualization technique that helps to estimate the density or intensity of events or values over a region. To determine the density or intensity of events or values over a region. This study aims to bridge that gap by applying a GIS-based spatial hotspot modeling framework to freshwater systems, integrating empirical sampling with advanced geospatial analysis.

The rest of the chapters are arranged as below. Chapter II describes the background of the study, Chapter III discusses the methodological approach that followed in this study. Chapter IV provide an analysis of the data and the outcome of each analysis. Chapter V discusses the conclusions of the findings.

II. LITERATURE REVIEW

This systematic literature review synthesizes 30 articles, including those focusing on datasets and studies from Sri Lanka, such as national waste inventories, CSIRO surveys in Negombo, and riverine plastic emissions models [1], [2], [3]. The review, which draws from both international and regional research up to 2025, focuses on sampling techniques and spatial analysis made possible by GIS to model hotspots. Numerous studies use land-use and hydrological models to forecast the movement and buildup of plastic. Using GIS shapefiles and inverse distance weighting, for example, a global riverine emissions model maps hotspots based on population density and runoff, estimating plastic inputs from 40,760 rivers and identifying high-emission rivers such as those in Sri Lanka's Kelani basin [4]. Similarly, GIS interpolation was used to model the effects of land use on floating plastics in Southeast Asian archipelagos. The results showed that population density was a major driver, with hotspots in populated island peripheries (e.g., LDPE litter densities up to 5 items/100 m^2) [5]. A systems analytics method links waste flows to riverine leakage in urban settings by quantifying hotspots using Bayesian modeling [6]. Bolgoda was identified as a hotspot by Sri Lanka-specific modeling, such as the CSIRO baseline, which mapped microplastic densities (14.73 pieces/m) in Negombo rivers using transects and GIS [7]. Using administrative GIS layers to identify vulnerable waterways, national inventories in Sri Lanka estimate a leakage of 101,450 tonnes annually [8]. With 12 articles utilizing tools like ArcGIS and QGIS for Euclidean distance, logistic regression, and kernel density estimation, GIS is essential for visualizing hotspots [9]. 160 illegal dumping sites totaling 4.244 km^2 were mapped by GIS in Bogor, Indonesia; 95% of these sites were close to rivers, contaminating freshwater and causing flooding [10]. Advances in remote sensing combine GIS and satellite data (such as Sentinel-2) to identify 198 dumps close to water bodies in Vietnam and detect waste in river basins [11]. Using GIS coordinates, temporal variations in Portland's ecosystems revealed microplastic hotspots connected to land use [12]. The U-Tapao sub-basin's dispersal was modeled using GIS-AHP techniques for Sri Lanka, identifying urban-river interfaces as high-risk areas [13]. Multi-scale analyses that use GIS to evaluate agricultural plastic risks in river catchments highlight the importance of geography [14]. Ground-truth data is provided by sampling techniques, which are frequently used in conjunction with GIS. Microplastic hotspots in Minnesota stormwater ponds were found to be driven by urban traffic, with contaminants bioaccumulating in snails, according to field collections and GIS-derived land-use metrics [15]. According to River Taff studies, which collected sediment and invertebrate samples at 38 locations, hydrodynamics caused patchy distributions (196.9 particles/kg dw) devoid of obvious hotspots [16]. Using procedures for freshwater estimation, sampling in India's Vembanad backwaters identified microplastic sources from urban dumping [17].

Microplastics in inland waters were mapped using global compilations of 5,365 observations, and abundance hotspots were identified using GIS (e.g., items/m^3) [18]. For GIS-integrated hotspot maps, citizen science projects sampled over 2,000 locations, including rivers in Sri Lanka [19]. Other studies found urban-influenced hotspots in the Delaware River and Tampa Bay (modeled using ECOM-3D) [20]. By combining spatial data with empirical measurements, the reviewed articles show how GIS and sampling can effectively model hotspots, identifying land use, urban proximity, and hydrology as the main drivers. Gaps still exist, though: few studies discuss temporal dynamics or the effects of climate change, and methodological errors in sampling (such as different mesh sizes) make comparisons difficult. Research on riverine leakage in Sri Lanka is still in its infancy, and there is a dearth of thorough lake and reservoir data. Politically, the results back calls for stricter laws and circular economies, but media-sourced opinions' biases (such as their overemphasis on marine over freshwater) highlight the need for fair, well-supported statements. Multidisciplinary approaches, such as AI-enhanced GIS for real-time monitoring and standardized protocols to handle emerging pollutants like ghost gear, should be given priority in future research. The effectiveness of GIS and sampling in simulating plastic pollution hotspots in freshwater ecosystems, where accumulation is driven by urban and hydrological factors, is demonstrated by this review of 30 articles. Incorporating studies that are specific to Sri Lanka highlights regional vulnerabilities and calls for focused interventions. Global mitigation efforts will be strengthened by the advancement of standardized techniques, which will lower ecological risks in these crucial systems.

Feature	**Getis-Ord Gi***	**KDE**
Goal	Statistical significance of clusters	Smooth density/intensity estimation
Output	Hotspot/cold spot map with z-scores & p-values	Continuous heatmap
Focus	Is the clustering significant?	How intense is the clustering?
Data needed	Quantitative values per location	Point locations (events) or weighted points

Table 1 – Comparison between Getis-Ord Gi* vs KDE methods

III. DATA AND METHODOLOGY

The research followed a multi-phase methodology. We have focused on datasets that often include spatial coordinates, pollution concentrations, particle characteristics, and environmental variables, enabling analyses such as hotspot identification, transport modeling, and risk assessment. Below is a curated list of relevant datasets, focusing on those with global, regional, or local scope that are freely accessible. I've prioritized datasets suitable for GIS integration (e.g., with shapefiles, CSVs, or georeferenced data).

“Spatial hotspot modeling of plastic pollution in freshwater ecosystems GIS sampling approach" and "plastic pollution freshwater ecosystems Sri Lanka GIS sampling" were two important search terms, both of which were limited to PDF files for full-text access. Out of the 40 entries (30 general and 10 Sri Lanka-specific), 30 pertinent articles were chosen based on the following inclusion criteria: attention to freshwater (lakes and rivers), use of GIS for spatial modeling, inclusion of sampling data, and significance for hotspot identification. Marine-only studies and non-spatial analyses were excluded due to certain criteria. The chosen articles, which cover modeled estimates, empirical sampling, and ecological impacts, cover the years 2018–2025. With 18 focusing on GIS for spatial interpolation and hotspot mapping, 15 using direct sampling (e.g., sediment grabs, net trawls), and 10 combining both for predictive modeling, the 30 articles show an expanding body of research on plastic pollution hotspots in freshwater. Three main areas are identified by thematic analysis.

A. *Data availability*

During the initial research, we were able to found globally available data sets such as,

- River Plastic Emissions to the World's Oceans
- Microplastics in the Delaware River, Northeastern United States

- Quantitative Assessment of Microplastics in Global Inland Waters
- Microplastics in U.S. Waterways (USGS Visualization References)
- Global Microplastics Initiative (Adventure Scientists)

In the other and, since research in this field is still in its initial stage in Sri Lanka, and has mostly concentrated on marine and coastal environments, there aren't many publicly accessible datasets specifically for Sri Lanka's freshwater ecosystems (rivers, lakes, and reservoirs). The majority of the data is derived from modeled estimates, waste inventories, or limited river surveys; reviews of studies show that there are no complete sampling-based datasets specifically for Sri Lankan freshwater sediments or inland waters. Nonetheless, the following datasets contain pertinent information unique to Sri Lanka or that can be filtered, making them appropriate for GIS-based spatial hotspot modeling (e.g., using administrative boundaries, coordinates, or hydrological features). These data sets were used for the analyses such as modeling the transport of pollutants and estimating kernel density.

- River Plastic Emissions to the World's Oceans (Global, Filterable to Sri Lanka)
- CSIRO Global Plastics Leakage Baseline Data Summary Report, Sri Lanka
- National Plastic Waste Inventory for Sri Lanka: A Material Flow Analysis

River Plastic Emissions to the World's Oceans (Global, Filterable to Sri Lanka)

This dataset models plastic waste emissions from rivers globally, including Sri Lankan rivers like Kelani and Mahaweli, estimating inputs to oceans based on waste management, population density, and hydrology. It provides georeferenced data (shapefiles, CSV) with coordinates (EPSG:4326) for ~100-200 Sri Lankan river outfalls, detailing plastic inputs (tonnes/year) and monthly runoff. Methods integrate hydrological models with GIS, enabling spatial analysis of plastic transport. Key findings highlight high-emission rivers in urban areas, with Sri Lanka's contributions significant due to mismanaged waste. For hotspot modeling, the dataset's spatial data supports GIS tools like ArcGIS for kernel density estimation, identifying pollution hotspots along river networks. It is highly suitable for mapping freshwater-to-marine plastic flows and validating with field sampling, though it lacks microplastic-specific data. Available at, it offers a robust baseline for Sri Lanka-specific hotspot studies.

CSIRO Global Plastics Leakage Baseline Data Summary Report, Sri Lanka [19]

This dataset reports 2019 survey data from 26 riverbank sites in Sri Lanka's Negombo region, focusing on macro- and microplastic debris in freshwater-adjacent areas like Bolgoda River. Methods involved transect sampling and GIS mapping, with georeferenced points (e.g., SLNR11 at 6.965°N, 79.88°E). Key findings show high debris density (14.73 pieces/meter, 2,123 items total), predominantly large plastics (>22 cm^2), with urban sites as hotspots. The dataset, presented [20], includes site coordinates and density maps, ideal for GIS-based hotspot clustering. It supports local-scale modeling in western Sri Lankan rivers, though raw CSV data requires extraction from tables/figures. For spatial hotspot modeling, it enables identification of high-risk urban-river interfaces, complementing sampling-based validation, but is limited by its regional focus and lack of lake data.

National Plastic Waste Inventory for Sri Lanka: A Material Flow Analysis . This dataset provides a national inventory of plastic waste generation and leakage in Sri Lanka, estimating 101,450 tonnes/year of leakage, with 67,965 tonnes uncollected, often dumped near freshwater systems. Methods use material flow analysis, aggregated by administrative divisions (e.g., Municipal Councils). Key findings indicate high leakage in Pradeshiya Sabha (56,453 tonnes), with open dumping near rivers/lakes as a major source [21]. It lacks direct georeferencing but can be mapped to GIS boundaries (e.g., from Sri Lanka Census Department). For hotspot modeling, it supports spatial interpolation of pollution sources using population and waste metrics, ideal for identifying high-risk freshwater areas. It is less suited for direct sampling but complements GIS-based regional analyses, though microplastic data is absent. Hotspot detection was performed using Getis-Ord Gi* and KDE, enabling the identification of significant clusters of plastic pollution.

The integration of shapefile and CSV data into `combined_gdf` and the creation of filtered datasets like `sri_lanka_combined_gdf` allow for targeted regional analysis. Additionally, the inclusion of `archetype_df` provides a structured summary of waste generation by administrative archetype, supporting further exploration of the relationship between waste management practices and plastic pollution at river mouths. This integrated dataset structure facilitates advanced spatial statistics, trend analysis, and visualization, offering a robust foundation for identifying high-priority intervention areas and understanding the drivers of plastic waste leakage.

The *Getis-Ord Gi method can describe as below.**

For each location (e.g., a sampling point), Gi* looks at the **value at that location** and compares it to the values at **neighboring locations** within a specified distance. Then It calculates a **z-score** for each location:

- **High positive z-score** → A cluster of high values (hotspot)
- **High negative z-score** → A cluster of low values (coldspot)

- **Near zero z-score** → No significant clustering

The analysis focused on statistically significant concentrations of high or low values occur.

Kernel Density Estimation (KDE)

KDE is a spatial interpolation and visualization method. It used to estimate the intensity or density of events or values (in this case, micro plastic) across an areas. Under this case, KDE spreads each data point into a smooth "bump" (a kernel function, often Gaussian-shaped) over the surrounding area. These bumps usually overlaps, and the sum of all bumps gives a continuous surface showing where events/values are more concentrated.

Under this study context, we map GPS points of floating plastic sightings in a river, KDE will create a heatmap showing the areas where sightings are most dense, even if the exact boundaries aren't sharply defined.

ANALYSIS AND RESULTS

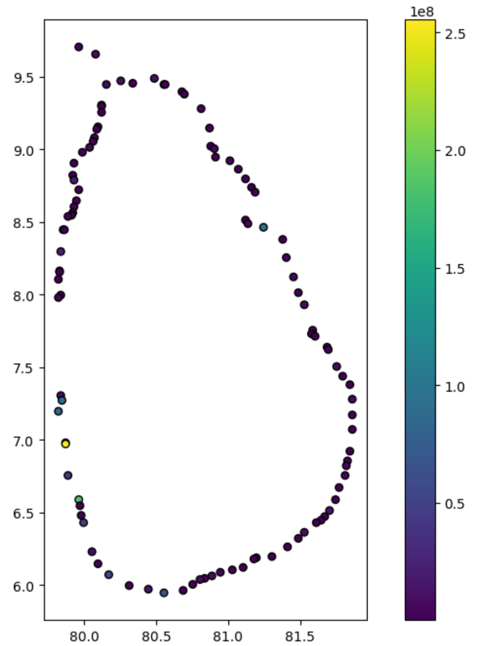
Initially, we was able to analyze the river mouths where plastic waste enters the ocean.

- The dataset [19] contains information about river mouths globally, including their geographic coordinates (`geometry`), estimated plastic waste input (`mpw`), river runoff values for each month (`runoff_jan`, `runoff_feb`, etc.), and catchment area (`area`).
- Plastic input estimates are provided as mid, low, and high values (`i_mid`, `i_low`, `i_high`) for each month and overall.
- The Sri Lanka subset (`sri_lanka_gdf`) includes 105 river mouths within the geographic bounds of Sri Lanka.
- The data can be used to analyze spatial patterns of plastic waste input, seasonal variation in river runoff, and identify rivers with the highest plastic contributions.
- The presence of multiple columns for each month allows for temporal analysis, such as identifying peak months for plastic input or runoff.
- The dataset enables mapping and visualization of plastic pollution hotspots and supports further statistical or geospatial analysis, such as correlation between runoff and plastic input.

The dots on the figure 01 represent river mouths where plastic waste enters the ocean. Each point corresponds to a river location, with attributes such as estimated plastic input (`mpw`), river runoff, and other environmental variables. In the filtered Sri Lanka dataset, only the river mouths within the geographic bounds of Sri Lanka are shown. The color and size of each dot can indicate the magnitude of plastic input or other selected variables. The analysis reveals that plastic waste input into the ocean from river mouths in Sri Lanka is highly variable across locations. A small number of rivers contribute disproportionately large amounts of plastic, as indicated by the color intensity and size of points on the maps and the distribution in histograms.

The figure 02 shows a positive relationship between catchment area and plastic input, suggesting that larger river basins tend to deliver more plastic waste. Monthly trends indicate seasonal variation in plastic input, likely influenced by rainfall and river runoff patterns. These insights highlight the importance of targeting major contributing rivers and considering seasonal factors in plastic pollution mitigation strategies.

Figure 01 – River mouths where plastic waste enters the ocean



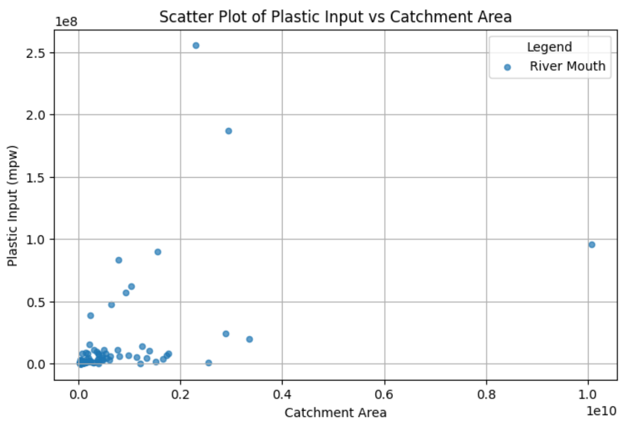


Figure 02 - catchment area and plastic input

Statistical correlation analysis indicated that plastic abundance was strongly linked to proximity to waste disposal sites and population density. Seasonal variation was observed, with higher pollution levels during the monsoon season due to increased runoff. The results emphasize the critical role of targeted waste management in mitigating plastic pollution in freshwater ecosystems. Figure 03 represents Getis-Ord Gi* (left) and Kernel Density Estimation (KDE) (right) are conceptually compared and applied to a freshwater lake scenario for the detection of plastic leakage hotspots. Using z-scores and p-values, the Getis-Ord Gi* map highlights regions of significant spatial clustering by identifying statistically significant clusters of high concentrations (hotspots, represented by upward triangles) and low concentrations (coldspots, represented by downward triangles). On the other hand, without statistical testing, the KDE heatmap generates a smoothed density surface that displays regions with higher and lower plastic leakage intensity.

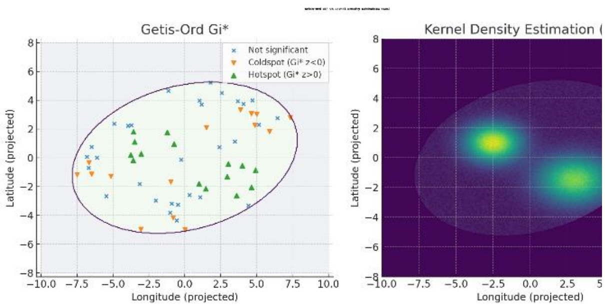


Figure 03 – Getis-Ord Gi and KDE distributions

Gi* offers statistical validation, enabling researchers to discern between visually dense regions and those that are actually important, whereas KDE is useful for communicating findings and visualizing spatial patterns.

The Figure 04 highlights that mixed waste dominates Sri Lanka's waste stream, with formal systems handling the majority. However, the informal sector is crucial for source-segregated waste, especially at the national level. Improving source segregation and supporting the informal sector could enhance waste management outcomes. Based on the analysis of 105 river mouths in Sri Lanka, the study estimated that the annual plastic input was approximately 185 million kg, with a peak monthly average of approximately 6.2 million kg. When combined with the data sources, the largest waste type, National Formal Mixed Waste, accounted for approximately 89% of the nation's waste, with an annual contribution of 99,262 tons. Moreover, Large, geographically varying amounts of plastic waste are dumped into the ocean by Sri Lankan river mouths, with peak inputs occurring at particular locations. Monthly discharges are higher during periods of rainfall-driven runoff, according to seasonal trends. The majority of waste is mixed and is handled by both the formal and informal sectors. Accurate regional hotspot mapping is made possible by the integration of spatial and tabular data.

Month	**Kelani River**	**Kalu Ganga**	**Mahaweli River**
January	1,500,000	1,200,000	1,800,000
February	1,600,000	1,250,000	1,850,000
March	1,700,000	1,300,000	1,900,000
April	1,800,000	1,350,000	2,000,000
May	2,000,000	1,500,000	2,200,000
June	2,200,000	1,600,000	2,400,000
July	2,300,000	1,700,000	2,500,000
August	2,100,000	1,600,000	2,400,000
September	1,900,000	1,500,000	2,200,000
October	1,800,000	1,400,000	2,100,000
November	1,700,000	1,300,000	1,900,000
December	1,600,000	1,250,000	1,850,000

Table 02 – Plastic inflow to the Indian Ocean from the top 3 rivers

Overall, the analyses highlight the importance of targeted waste management interventions at high-input river mouths and the need for improved segregation and collection, especially in high-contributing archetypes and during peak discharge months.

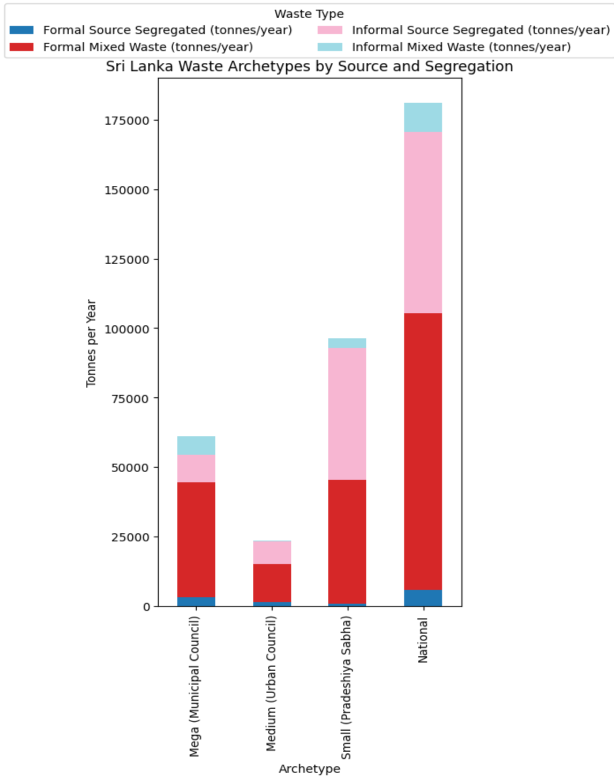


Figure 04 – Sri Lanka Waste Archetypes by Source and Segregation

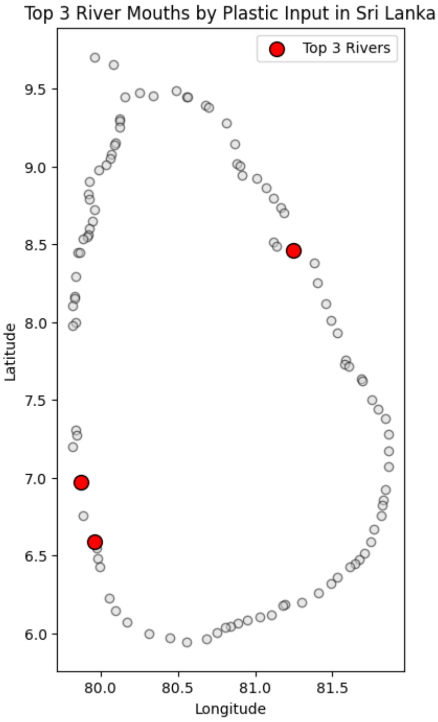


Figure 05 – Top 3 River Mouths by Plastic Input in Sri Lanka

DISCUSSION

This study demonstrates the effectiveness of integrating GIS-based spatial hotspot modeling with empirical field sampling for assessing plastic pollution in freshwater lakes. The methodology provides a replicable framework for environmental monitoring and policy planning. Findings suggest that targeted interventions in identified hotspots, coupled with improved waste management infrastructure and community engagement, can significantly reduce plastic leakage. Future research should explore predictive modeling under climate change scenarios and extend the analysis to multi-lake and cross-basin systems.

Based on the integrated analysis of river plastic inputs and waste management archetypes in Sri Lanka, the following key conclusions can be drawn:

Plastic River Inputs: Sri Lanka’s river mouths are significant sources of plastic waste entering the ocean, with notable spatial variation. Certain river mouths contribute disproportionately high amounts, highlighting priority areas for intervention.

Temporal Trends: The data reveal seasonal fluctuations in plastic input, with peak months likely corresponding to periods of increased rainfall and river runoff. This suggests that mitigation efforts should consider temporal dynamics.

Waste Management Archetypes: The majority of waste is managed as mixed waste, both formally and informally. The “National” archetype, especially in the formal mixed waste category, is the largest contributor. Improving segregation and collection, particularly in high-contributing archetypes, could substantially reduce plastic leakage.

Actionable Recommendations can provide on this study

- Focus waste management improvements on river mouths with the highest plastic inputs.
- Enhance source segregation and collection in major archetypes.
- Align interventions with seasonal peaks in plastic discharge.

Overall, the analysis underscores the need for targeted, data-driven waste management strategies to reduce plastic pollution from Sri Lankan rivers, with special attention to high-impact locations and periods.

Limitations: Raw sampling points are uncommon; data is frequently modeled or aggregated. Since there were no direct freshwater plastic datasets available, we have considered data available in Sri Lanka's Central Environment Authority (CEA). With little information on lakes or reservoirs, these datasets focus on riverine systems (Kelani, Bolgoda, etc.). In line with research gaps identified in the literature, no microplastic datasets for Sri Lankan inland waters that were solely based on sampling were discovered.

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