# Fate of Non-Recyclable Plastic Wastes: Material Flow Analysis, Leakage Hotspot Modelling, and Management Strategies

**Aprilia Nidia Rinasti** (aprilianidia@ait.ac.th)
Asian Institute of Technology
**Indradhi Faisal Ibrahim**
Asian Institute of Technology
**Kavinda Gunasekara**
Asian Institute of Technology
**Thammarat Koottatep**
Asian Institute of Technology
**Ekbordin Winijkul**
Asian Institute of Technology

**Article**

**Keywords:** plastic pollution, morphometric analysis, leakage analysis, material flow analysis, urban area

**Posted Date:** June 3rd, 2022

**DOI:** https://doi.org/10.21203/rs.3.rs-1611355/v2

## Abstract

Low priority on waste management has impacted the complex environmental issue, where this study found out up to 24.3% of waste generation in Jakarta and Bandung is emitted to the waterway due to the high intensity of human activity in the urban area. In this study, we investigated the viable integration between material flow analysis and leakage hotspot modelling to improve the management strategy of the plastic pollution in the water system and open environment. Using the multi-criteria assessment through the plastic leakage from its management, a material flow analysis has developed on the city scale. Comprehensively identifying using potent identification and hydrological characterization, plastic waste from Jakarta city has occasionally estimated 2603 ton discarded to *Ciliwung* River while the plastics from Bandung Area has contributed to 1547 ton, addressing *Cikapundung* River as the main tributary of *Citarum* mainstream in annual basis.


## 1. Introduction

Plastic waste has overwhelmed and grown rapidly across the nations, which is estimated to increase doubled in 2050 [1]. Therefore, an option to reduce the existing and upcoming plastic waste is recycling which also reduce the usage of oil, carbon dioxide emissions and disposal [2]. Although recycling is an available method to reduce the impacts of plastic industry [3], yet approximately only 9% of plastic waste had been recycled [1]. The presence of non-recyclable plastic has also decreased the recycling rate, for instance, thermosetting plastic [4], thermoset composite [5], and multilayered plastic [6]. Moreover, some recycled plastics are not as environmentally friendly as virgin plastics due to the additives in the products such as stabilizers, and flame retardants [6]. In addition, although many plastics are classified as recyclable, the price is not always economically valuable since its driven by both supply and demand in the recycling market [7]. Comprehension of non-recyclable plastic in term of prevent leakage of these plastics into the ocean.

Other than recycling issue, exceeded amount of plastic waste in the environment has been implicated in its presence in the water system on the sub-basin level [8] [9] and riverine plastics [10]. Highly amount of the plastic waste in the water system has been developed by utilizing spatial analysis using Geographic Information System (GIS) through three pillars of sustainability identification aspects [11] [12], developing waste management scenarios by monetization on the economic condition [13] [14], implying the seasonal changes [15] and adapting the hydrological model [16]. The amount of plastic waste leakage also has been developed to the remote sensing technologies as the monitoring implication towards the discarded plastics on the aquatic and terrestrial environment using UAV [17] [18] and satellite-based monitoring [19] [20] [21] [22]. Some approach has been made for integrating the waste management system using spatial analysis using GIS [11] [23] [24] to maximize the system and capability on the management. Shortly, the ever discarded of the plastic waste in the open environment has been developed by the direct existing condition without the source identification.

Meijer et al. [9] reported that Indonesia contributed about 5.6 x $10^4$ million ton per year of plastic wastes into the ocean (ranked 5th on the top 20 annual plastic emission countries). As a response, the country issued Presidential Decree No.97/2017 (National Waste Management Policy and Strategy) [25] that aims at 30% waste reduction and 70% waste handling by 2025. In particular, Presidential Decree No.83/2018 (Marine Debris Management) [26] has also been enforced to reduce 70% of marine plastic debris by 2025 through tax, the roadmap of waste reduction by producers, standard operating procedure of waste management in marine tourism destinations activities, alternative use of plastic waste, and the international agreement on the cross-border plastic waste handling issues. Unfortunately, the implementation of the reduction target is considered not accomplished, one of the reasons is insufficient recycling capacity, in which the country needs to double the current recycling capacity to process 975,000 ton per year more of recycled plastic by 2025 [27]. According to the Indonesian Plastic Waste Recycling Association (ADUPI), recyclers are often unable to obtain appropriate plastics for their industry [28].

For the solutions, Indonesia is sanguine to pledge the producers by implementing design for sustainability (DfS) to prevent and limit the plastic waste generation [29]. Indonesian government also has flourished to use plastic waste as the mixture for road construction [30]. Compliance with the example in Japan, plastic that unable to be recycled into raw materials is managed through the chemical recycling and thermal recycling such as gasification and refuse derived fuel (RDF) [31], while India used RDF and plasma pyrolysis technology [6]. These efforts have been introduced and implemented generated by the whole management system by implying the 'closing-the-tap' concept, which prevailed by managing the residue from waste management.

Although the effort on the recycling plastic waste has been utilized tremendously, some issues have not been addressed where leakage term also accommodates recycling stagnancy [7]. Therefore, the calculation through each stage of the waste management spatially has not developed yet to encompass the presence of plastic waste in the environment. One of the closest approaches has been made by improving the country level [14] and city-level data of waste management [12] on the consumption level. To comprehend the analysis of material shifting on the existing waste management, integration between the concept of material flow analysis and the spatial domain study to enhance the concentrated leakage amount as one of the systems approaches to integrate solid waste management was applied. Waste management stages imply an increment study on the assessment of the waste [32], which is also suitable to integrate with spatial analysis using GIS [33] [34].

In compliance with the solutions, initially we define non-recyclable plastic waste (NRPW) as plastic waste that cannot be recycled by the current recycling practice in the specific area because of technological hindrances and poor management. The technological hindrances are in consequence of the absence of technology, complex plastic polymer structure, and/or environmental reasons due to potential pollution caused by recycling activity. Meanwhile, poor management such as no segregation waste system, open burning, littering, and/or any activity that can turn plastic to a non-recyclable due to low quality or low economic value. In this study, we calculate the amount of plastic waste leakage using the material flow analysis assessment and distinct the NRPW according to the definition. Then, we aligned the predicted situation from where it was generated to the final discarded to the water system. The GIS was utilized to perform the location-based analysis towards the distribution of the leakage and its pathway based on the hydrological condition. Thus, the main objective of this study is to improve the measurement of the NRPW leakage and its leakage pathway from the source to the river.

## 2. Results

## 2.1 Material Flow Analysis of Plastic Waste (2021)

Material flow analysis both in Jakarta and Bandung was developed to study the plastic waste before categorized as the NRPW. Result shows the plastic waste generation in Jakarta was 399,691 ton/year from 10,534,339 people [35], 0.7 kg/capita/day of municipal solid waste (MSW) generation rate [36], and 14.85% of plastic waste in MSW [37]. Jakarta's plastic waste composition consisted of 5.85% of PET and 9.00% of mixed plastic [37]. Meanwhile, for Bandung with population of 2,584,252 people [38], the MSW generation rate and the percentage of plastic waste are 0.63 kg/capita/day [38] and 22.45% [38] of plastic fraction. This plastic composition consisted of plastic bottles, plastic glass, plastic wraps & multilayered, plastic containers, plastic bags, and diapers. Therefore, plastic waste generation in Bandung is 133,409 ton/year. Figure 1 contains the material flow of plastic for both areas.

In terms of plastic waste collection at the source, 44,281 ton/year (11%) was uncollected in Jakarta, while 326,829 ton/year (82%) and 28,581/year ton (7%) of them were collected by collection services and informal value chain. In Bandung, 12,512 ton/year (10%) of plastic waste was not collected. Then 93,973 ton/year and 26,924 ton/year were collected by collection services and informal value chain (70 and 20%, respectively). Informal value chain is related to the informal waste pickers (e.g. scavengers) commonly collecting the waste at the streets and disposal sites. Managing after the collection, the collection services diverted to the sorting facility for recovery about 106,043 ton/year and 12,300 ton/year in Jakarta and Bandung, respectively. Jakarta's higher percentage was supported by waste sorted for energy with a capacity of about 100 ton/day [36] which also improved the realization of 34% of plastic waste possible to be recycled as the energy form [39]. Respectively, 95,926 ton/year and 36,500 ton/year were sorted from pre-treatment facilities for recycling and energy from wastes in Jakarta. On the other hand, 38,436 ton/year of plastic waste was sorted for recovery (e.g. mechanical recycling) without waste to energy in Bandung. Further, a total of 211,309 ton/year of plastic waste was transported by Jakarta's municipality to final disposal in Bantar Gebang, Bekasi City. In Bandung, 78,570 ton/year of plastic waste was disposed in Sarimukti, West Bandung District.

From both cities, leakage is based on the uncollected waste and residual term of management stages. Jakarta was responsible for 28,472 ton/year of plastic waste entering the waterway across five cities. On the other hand, Bandung discharged the plastic waste of approximately 10.945 ton/year to the waterway. Most of the plastic waste leaked to the waterway was sourced from the direct disposal where Jakarta acquired 57.6% and Bandung at 56.08% of the total waterway leakage, delivering the first phase of investigation on the human activity as the contributor of litter [40]. Demonstrate the main contribution of plastic debris into the waterway is the land-based source [12] [13] [41] through direct littering due to inadequate waste management system.

## 2.2 Quantity and Composition of Non-Recyclable Plastic Waste Leakage

Plastic waste leakage from an uncollected waste was the largest contributor in both areas, yet we also considered the leakage from other waste management activities. During the collection activities, there were 9,477 ton/year from collection services and 257 ton/year from the informal value chain in Jakarta. On the other hand, 3,101 ton/year and 215 ton/year were leaked sequentially from the collection services and informal value chain in Bandung. Apart from collection, disposal facilities in both areas added the leakage by 4,248 ton/year in Jakarta and 7,910 ton/year in Bandung. Despite of higher disposed plastic waste in Jakarta than Bandung, the leakage from disposal facilities were less since we put lower leakage potential levels from environmental hazards (e.g. flooding or landslides) and fencing in the WFD tool. For example, we found the treatment and environmental management were adequate in Jakarta's final disposal and treatment facility, which is called TPST Bantar Gebang [42]. In terms of sorting facilities, formal sorting (e.g. waste banks) in both Jakarta and Bandung do not contribute to plastic leakage since the waste banks sorted out the valuable plastics at the source. As a results, the amount of reject from waste banks are very low and back to the formal collection system. On the contrary, 1,941 ton/year and 573 ton/year of plastic waste were leaked from informal sorting in Jakarta and Bandung, respectively.

When the plastic waste entered the environment, 4,622 ton/year was burnt and 25,770 ton/year was retained on land, while 13,403 ton/year and 16,409 were respectively entered drainages and the Jakarta's River systems. Further, 1,340 ton/year was retained on the drainage systems, while the rest of 12,063 ton/year was discharged into the waterway. Hence, a total of 28,472 ton/year of plastic waste was leaked into the waterway in Jakarta. When disposable diapers took into account, the number increased to 40,880 ton/year since its responsible for about 30% [43] of the total waterway waste leakage composition in Jakarta. We also included disposable diapers in this study since they were considered as a NRPW. In Bandung, it was counted that 1,071 ton/year, 11,990 ton/year, and 5,113 ton/year of plastic waste were leaked into the air through open burning, retained on land, and entered the storm drains, respectively. Moreover, plastic waste was littered directly into the river about 6,139 ton/year. Therefore, 10,945 ton/year of plastic waste was leaked into the waterway in Bandung. In other words, the ratio of plastic waste littering per person in Bandung and Jakarta are, respectively, 3.88 kg/year and 4.24 kg/year.

From the total plastic waste leakage into the waterway, we estimated the amount of NRPW in both cities, which were 37,995 ton/year (9.51% of total plastic waste generation in the city) in Jakarta and 10,636 ton/year (7.97% of total generated plastic waste in the city) in Bandung. Plastic bottles and plastic cups are not included as non-recyclable plastic due to the availability of the recycling facilities and their relatively higher economic value which is different from the disposable diapers, multilayered plastic packaging, plastic bags, and other plastic. In Jakarta, plastic bag was identified as the most NRPW in the waterway with 20,777 ton/year, the fact that waste is frequently disposed of inside plastic bags. This followed by 12,408 ton/year of disposable diapers, 3,944 ton/year of plastic packaging, and 866 ton/year of other plastic respectively. Meanwhile, in Bandung, plastic bags and diapers were discovered as the most NRPW in the waterway with the same amount of 3,477 ton/year. Further, it is followed by 2,215 ton/year of plastic packaging and 1,468 ton/year of other plastic respectively. Based on our model, the composition of NRPW in the waterway for both Jakarta and Bandung is shown in Fig. 2.

## 2.3 Potential Leakage Hotspot Identification

With the waste generation from the overall population in each city, Jakarta has discharged 37,995 ton per year, and Bandung discharged 10,636 ton per year to the waterway. Based on the identification using Waste Flow Diagram tool, both cities indicated the most leakage from the overcapacity of waste management facilities. Therefore, we consider the amount of the hotspot leakage based on the residual term and topographical feature related to the location of the facilities. On the other hand, the leakage also implied from the uncollected term, which lead to the possibilities of direct disposal of plastic waste to the water system–which regarded as the NRPW. Therefore, limited by the residual and direct disposal, both cities respectively implied the possible amount of water leakage distribution in Fig. 3 in the accumulated ton in an annual basis.

We found that over 225 hotspots which came from the waste management facilities in Jakarta, indicating 24.3% of the waste management are responsible for the potential leakage source which contributes to the river pathway. Due to the method of facilities assessment and its proximity to the river pathway, spatial distribution indicates 39.12% of the facilities are in the high-zone proximity (0 – ≥100 m) and 7% of the facilities obtained fully potential to the leakage on an annual basis. Most of the contributor of the facilities prominent in *Dipo* types (transfer station in the community level), which also depends on the zonal coverage. The second contributor were *TPS 3R* (3R station for material recovery), which exceeded 61.3 ton per year; indicating how the concept of *TPS 3R* needs to be improved in Jakarta [44]. On the other hand, we assumed the management of waste bank has effectively managed with zero leakage based on the calculation and assessment through the spatial approach. This Implied that the collection at the source and the current management are in the good prospect of Jakarta waste management [45].

Another source of the leakage in Jakarta area was from the plastic waste generation in the residential area, which was also responsible to the 36.76% of the contribution in the final disposal [46]. Limited to the population settled in the riverbank area, approximately 2,080,076 population (19.7% of total population in Jakarta contributes 28.944 ton/year of plastic waste at the source. We found the potential of the direct disposal term due to the cramped population at the wards in slum categorized exceeding 87,696 population or 42% of the population settled on the proximity of the river pathway in between 0 to 300 m buffer area from river centroid across the city.

In Bandung, there were 122 waste management facilities contributing to the leakage in Bandung. Based on the same method for the residual leakage, we found 25 facilities are high in leakage probability, where 14 of the facilities are located close to the riverbank area (100-meter proximity). Although the leakage hotspots in Bandung are half of the Jakarta, the leakage exceeds 120.85 ton in annual basis for the minimum leakage (Jakarta is 61.3 ton/year). Based on an assessment on the spatial range, we found 25 facilities potentially contributing to the waterway as the possibilities to the leakage. In short, Bandung is comparable with Jakarta in term of leakage to the waterway according to its proportion; where Jakarta contributed the leakage of 61.3 ton in annual basis from 24.3% possible sources, and Bandung is 120.85 ton in annual basis from 20.5% of possible sources of leakage. Therefore, its pathway as the mobilization of the leakage material needs to be concisely constructed from the water pathway.

Overlaid with the condition on the topographic condition and hydrological condition, the morphometric parameters utilized over 31.7% of the waterway in Jakarta are considerably high on the plastic leakage and 18.3% in Bandung. Correlating with the elevation, Bandung has higher differences in the elevation on the highland area, considering how the water flow are likely high in the mountainous area [47] which considered the higher chance of plastic waste leakage to shift to the other area. Comparing with Jakarta, which is in the coastal area and considerably flat, causing higher chance of access to the waterway.

Type of river distribution is also considered where both cities have different characterization of the mainstream; Jakarta has several mainstreams which likely non-concentrated area of the flow while Bandung has only one mainstream which all the streams in Bandung is from Citarum River in the Southern part, considered how the flow vary in terms of the accumulation of runoff to Citarum River.

## 2.4 Plastic Leakage Pathway and Seasonal Changes

Wrapping up the conclusion of flow characteristics judged based on the morphometric analysis towards the digital elevation model comprehend the full picture of the leakage mobilization in the waterway, shown in Fig. 4. The result shows that rainy season has fully implication on higher accumulation and less hotspot area. Therefore, an assumption on the quantification method in the hydrological characterization is applied to improve the retained material in the low runoff. According to the spatial distribution of the river network and the leakage source hotspot, 67 hotspots contemplate with river networks in Bandung uptakes the leakage contribution over 82.18 ton per year.And in Jakarta we found 742 locations contributes over 34.41 ton per year across the riverbank area.

Based on the distribution of river network, Jakarta exceedingly obtained 83 networks across the 5 cities and divided to 7 mainstreams which directly flow to the ocean from Jakarta Bay. In Fig. 4 (A), Jakarta obtains the leakage distribution more in the transboundary rivers (Western part directly adjacent with Tangerang and Eastern part with Bekasi) where potentially 442.58 ton in annual basis was input to the Mookervart River in West Jakarta and 165.51 ton in the Cakung River adjacent with Bekasi in North Jakarta.

According to the slum area assessed from BPS and KOTAKU [48], it shows the sparsely dense in Northern area of Jakarta. The slum area distribution is related to the leakage pathway since there are more plastic waste leakage to the river near the slum-graded wards. We found the higher leakage in the streams to Tanjung Priok port area of approximately 507.56 ton. This causes more evidence of high intensity of land and sea-based activity contributes on the plastic releases in annual basis in the same case with Jambeck's study (2015). It is also found how the intense activity on land causing higher intensity of leakage flow in the waterway [49]. Considering how the slum area also regarded to the higher population density lived in the riverbank area with poor-managed waste management [50] [51], proof the direct disposal and low-managed of waste management are still existing in developing country. It is also proven by the leakage load which is higher in the Northeast part of Jakarta [52] as slum area and higher activity. On the other hand, direct disposal also considered happened due to unrecorded and unidentified illegal dumping which also same in the African case studies according to Verster and Bouwman [53] ; prevalent to the low-managed area especially in slum categorized area, in extent need to be addressed as the leakage.

The distribution of plastic leakage pathway in Bandung (Fig. 4.B) shown the concentrated leakage found in the Southern part of the city which adjacent to Bandung Regency, lead the waterway to the mainstream of Citarum River (represent in dark-colored delineation line in Fig. 4 part B). As seen in in Fig. 4, the leakage pathway directed to the mainstream and obtained the higher amount of input to the river towards the tributaries in Citarum River. Here we found the higher concentrated input to the waterway in Cikapundung Kolot based on the surveyed in November 2021. Correlating with the classified river flow in Fig. 3B, the continuous low classified flow in the directions to Citarum defines how the lower flow lead to higher accumulation, causing the higher result input in the waterway. Thus, around 108.77 ton of plastic waste likely was forecasted to input to Citarum as the mainstream in an annual basis.

Comparing side-by-side, the leakage source hotspot in Bandung area (Fig. 3.B) with the leakage pathway in the river pathway (Fig. 4 part B),Western part of Bandung which also adjacent to the Cimahi City detected high concentrated leakage source hotspot.. This condition implies due to the wider zone of slum regarded area. The topographic condition is also affected the result from morphometric analysis.

Both Jakarta and Bandung condition of accumulation provided with the runoff, correlated with rainfall rate (see **Appendix Data S2**). We found that rainfall and flash flood identification (from the morphometric analysis and peak runoff correlation) considered where most of the mainstreams are responded highly to the leakage. Contextualizing the data from satellite-based precipitation [54] [55] and national weather station observation [56], the peak rainfall on both cities is high in period of November to May (see Appendix **Data S2 Fig. S3**), initializing the possibility of flash flood and fluctuations in plastic leakage to the river pathway.

Aforementioned higher rainfall rate in November to May period and respond to the higher input to the pathway, we found Jakarta exceedingly high in February which can be shown in Fig. 5. Both cities were high in the transitional period in May where potentially 826.52–1114.82 ton of plastic waste is discarded. We predicted that higher rainfall rate which causing the flash flood has correlation with the direct disposal tendency from residents in the riverbank area with low-managed of waste management.

As Jakarta obtain the immersed peak of leakage accumulation in February (Fig. 5) exceeding 2516.44 ton in one month to the overall waterway network in Jakarta, we investigated on the risk from higher rainfall rate (604.4 mm based on BMKG Kemayoran Meteorological Station [56]). Accordingly, we found the historical flooding events were peaked during the rainy seasons in Jakarta. Jakarta has occurred a long-time historical flood in February and spotted 1245 hotspots of flood from BPBD Jakarta [57]. It is also implied that the understanding on the tendency of direct disposal was higher during the rainy season in the riverbank area which affected the significant runoff in the waterway causing the flood. Based on the research in the same location in Jakarta [58] in period 2015–2016, the tendency of direct disposal was up takingly high due to the higher flow and remove the waste from the residential area faster. In short, the higher rainfall became the complex issue where higher disposal and occurrence of the flash floods–leading to enormous number of plastic waste discarded in the river.

A significant drop identified in Jakarta calculations from February to March, where we found roughly 820.31 ton during March. We assumed a short-term solution during this period due to the overwhelming condition in the previous month. As taken respond of the catastrophic, the authority designated a major cleanup of the river area and disaster response. According to the Environment Agency in Jakarta, they conducted a special form of *Pasukan Orange* to prevent the flood occurring and do more rejuvenation of rivers in Jakarta [58]. Therefore, we can conclude that the immediate act of plastic waste in short term can bring the significant impact and potentially lower the number of plastic waste in the river if a long-term act and predictive act across the systems can be enabled.

Similar to Jakarta area, the number of accumulations of plastic discarded to the river pathway are high during the rainy season period. As seen in Fig. 5, Bandung obtained the higher plastic waste in the river pathway during Ocotober to May. However, the extreme drop from May to June are alarmingly due to the sudden rainfall rate drop–which also a transition from rainy to dry season. This condition implies that the higher accumulation of plastic waste will happen in the rainy season. However, the higher disposal in the pathway can contribute to higheraccumulate accumulation of wastes in the dry season due to the lower runoff in the river. Therefore, we conclude that another cleanup activities needs to be implemented for the short-term solutions.

## 3. Discussions

Leakage from the different perspective Plastic waste, especially categorized as the non-recyclable plastics in this study–leaked to the open environment based on the several different perspectives and causal relationships. Firstly, from the current management. Based on the Result 2.1, shown the possibility of leakage according to the judgement of the current situation. Each waste management stage proved determine the contribution due to the received waste which has low recyclability. For example, plastic waste commonly found (from Result 2.2) such as disposable diapers, multilayered plastic packaging, plastic bags, and other plastic (e.g. toys) have no available recycling method in the cities and/or area surrounding both Jakarta and Bandung. Although recycling plastic bags and other plastics might exist through the capacity building in commune level [59] [60] [61] [62], yet it is not common practice due to the highly contaminated plastic disposed.

Secondly, from the location-based analysis. Based on the multi-criteria assessment and proximity analysis, no relocation needed for the waste management facilities nor residents in the riverbank area. Although the leakage term detected due to the residual and direct disposal, solution-based approach preferred from the sources. Therefore, to bottom-up the solutions, the treatment of facilities needs to be escorted. Comprehend from the higher contributor, 3R station (TPS 3R) is considerably needs to be improved. As it denoted to be part of waste reducing, maximizing in material recovery is scarce as Jakarta contemplates with Jakarta Recycling Center (JRC) management [63]. Taking the example from the non-existing leakage emitted from the waste bank, which improve from the source collection. This is also addressed the behavioral changes of human to deliberate with proper management for recycling [64]. Due to the success, the planning of waste bank distribution and raise the accessibility are preferred to decline the non-recyclable plastic exists.

Understanding Non-Recyclable Plastic Waste From the identification of the NRPW through the absence of the ability to be recycled, the content entails to wider variety of plastics. For instance, plastic bags and packaging in general categorized to mismanaged plastics if it disposed dominantly [14] [65] we conclude both of type as non-recyclable plastic due to the technology hindrances. With the unavailability of the methods for recycle, thus highly contaminated due to the low segregation at source causing the debilitating in packaging plastic life cycle [66]. As it implied to the higher leakage in the waterway due to its properties and unhinge consumption from the human activity [64], some actions are obligated such as passing out the multilayer plastics to escalate the plastic circularity.

Verification of Plastic Waste Leakage As model of NRPW leakage distribution obtained, a verification needed to improve the confidence level of the result. We conducted verification towards the result of concentrated area of the leakage source hotspot and number of forecasted leakages from the material flow analysis method. Robust direct survey location needed, due to the limitations of social distancing, we focused on the impactful area. However, we also recommend validation through optical remote sensing which can be utilized from open-source platform using mid-resolution satellite imaging.

To comprehend the amount of plastic leakage to the waterway, we compared our results to the previous year's report [43] and the most recent report [67] of plastic waste discharge in the waterway. Considering the Marine Debris Hotspot Synthetic Report [43] defined the problem similar to the terminology of NRPW discharge in non-tidal waterway and discharge of plastic waste due to mismanaged plastic waste [67], we found the proportion of each amount were shown in the Fig. 6 below. Our result obtained lower number compared to the same reports [67] which obtained 76.5% in Jakarta and 29.7% from Bandung area. We investigated the different approaches and understanding on the plastic waste and calculation, where [67] report applied the overall mismanagement of plastic waste and unspecified the plastic types. Therefore, the result is enormously higher than our result. Based on the Marine Debris Hotspot report [43] shows the ratio of 10:9 differences within 5-year gap of data.

Seasonal Pattern of Leakage to the Waterway As we concluded the amount of leakage during the rainy season obtained approximately 785.06–2516.44 ton per month for the five cities in Jakarta and 524.97–826.52 ton per month in overall area of Bandung City, substantially affected to the occurrence of the flood. Focusing on Jakarta as the higher number of occurrences of flood due to the low land level, extreme rainfall in February causing Jakarta prone to flood during this month. Referring the streamflow data over the past 15 years [68] [69] [70], shown the higher probability on the flooding events in February–which also improved by the morphometric analysis to refer the probability of flash flood occurrence [71]. Based on the data from [54] [55] [56] shown how Jakarta alerted in February and Bandung in November, causing the higher hazard on the certain period.

Due to the probability of flood period or higher chance on flash flood due to the high rainfall [72], we verified our evidence-based from the reported condition during the heavily rainy season in Jakarta, where February was predicted to be the anxious period [73] [74] due to the rainfall pattern since 2013. Recoded from the authority of Water Resources Services (DSDA) in Jakarta, from the observing portal called *Pantau Banjir Jakarta* shown along February 2021 12 of 20 floodgates and observation posts recorded hazard alert due to the water level [75]. Correlating with rainfall studies shown the flood inundation highly compensate from the higher rainfall rate [76], which is also aggravated the higher chances of flood by plastic abundance in the waterway especially in the settlement area [77]. We conclude that how there is an alignment of flood occurrence in Jakarta with the overwhelming plastics discarded, which enormous amount in the rainfall profoundly detected in the peak rainfall rate across the cities especially in North Jakarta area. Pointing out also the rainfall rate spikes in Bandung where plastic has been the blockage flow in Citarum tributaries [78] [79] proving how the accumulation were high during the transition from rainy to dry season.

Preferable Management for Non-Recyclable Plastic Waste Leakage Contextualizing with the number of leakages for NRPW in the river, we elaborate on the existing material from the composition analysis in both cities. To address the solution, management can be adapted in upstream and downstream management. We encourage the upstream management to reduce the amount of non-recyclable plastics such as design-for-recycling [80], which push the producers re-consider their products to be collectible, detectable, and recyclable [81]. According to interview with recyclers in Bandung, there is around 30% of plastic waste that rejected from recycling facilities due to bad design. Therefore, there is the opportunity for some producers to make their products recyclable. Another policy approach is choice editing concept, in which a response of government and retailers on what to (or not to) provide in the market through ban or levy the sustainable products. For example, plastic products such as personal care goods (e.g. sachet, food containers) shifted to refill or reusable packaging. Moreover, Extended Producers Responsibility (EPR) as a take-back system for producers to secure their products from high contamination of commingled waste is highly recommended. In Bandung, we estimate there is about 21,895 ton of NRPW that can be avoided through EPR in 2025. In fact, Indonesia has regulated EPR since 2008, yet there are still very few producers who have contributed. To support the implementation of EPR, Indonesia has elaborated the law with the Ministry of Environment and Forestry law No. 75/2019 on the roadmap of waste reduction by producers in 2019.

As leakage found highly in the North part of Jakarta and in West part of Bandung, a downstream approach could be the possibility of increasing the management [82] through the nearby higher leakage pathway. In the same extent, the existing littered NRPW still can be managed. Therefore, some solutions we have taken for NRPW practices. Current practices, Indonesia started implementing waste to material which encountered the brick substitution and waste to energy prevailing reduce derived fuel (RDF). As higher the non-circular plastic which unable to be circulate to the recycling or reusing appliances, approach to utilize plastic to brick has been flourished [83] and commune-level product of Ecobrick proved useable for non-strctural purposes [60] and passed the class 3 of National Standard [84]. Considering the urban sprawl in both cities, it is also deliberating with the location of industrial estate in between Jakarta and Bandung. Flourishing refused derived fuel could be an option for the sparsely density of urban cities which also has been implemented in Central Java [85]. However, the implementation in high density urban area like Jakarta still under consideration since the significancy on reducing plastic waste still dominated 66% to final disposal in Bantar Gebang [39].

Possible Improvement Our model identified the distribution of prone of higher leakage over the years which contemplate for direct actions in the high-risk locations. However, some of the considerations needed to enhance the reliability of the amount of leakage along the plastic value chain. We also recommend designing a direct sampling for the plastic leakage pathway in the river to concise the number of leakages, thus take the overall consideration of distribution regardless the communities. The dynamic changes for plastic leakage pathway changes due to the socio-economic aspects where human activity and management in the area, therefore the solutions needed to provide the citizen science input.

## 4. Conclusions

Non-recyclable plastic waste is potentially leaking to the open environment in massive number. From the composition analysis, leakage mostly detected from the natural hazard and consumption stage, which lead to higher concentrated leakage hotspot from the residual term and direct disposal tendency. Leakage source hotspot identified in both cities spur higher than 100 ton per year in one spot. Leakage pathway mostly detected in the slum settlement area and the curbside of the cities, involved the judgement of the current of waste management accessibility. Concluding with the enabled program for ever increasing NRPW, best management practices implied to applying the short-term solution with river cleanup and integrate the solutions in long-term by increase the recyclability of the plastics from the source.

## 5. Methods

This study was implemented in the two metropolitan cities in Indonesia: Jakarta and Bandung. Both cities have comprehensive systems on waste management due to the large amount of waste generation. Determining the waste management and spatial analysis in the city scale analysis, we applied the concept of material flow analysis through the Waste Flow Diagram (WFD) tool for plastic leakage quantification. Subsequently, an indexing system was used to improve the distribution towards the material shifting of the plastic waste in the open environment After the process was systematically analyzed for leakage pathway according to the topographical conditions.

# 5.1 Material Flow Analysis: Waste Flow Diagram

Plastic Waste Data on MSW Management In this study, we included the whole area for Bandung and Jakarta (excluding Kepulauan Seribu district from the Greater Jakarta Area) corresponding with the leakage modelling purpose. Jakarta is known as the capital city and the largest city in Indonesia, with a total area of 662.33 $km^2$ [86]. The area is divided into six municipalities, 44 sub-districts, and 267 villages. Bandung is the capital city of West Java province. It is divided into 30 sub-districts covering 151 villages, with a total area of 167.31 $km^2$ [87]. A set of data regarding waste management was collected and entered the WFD tool. At first, to estimate the plastic waste generation in both cities, the amount was calculated by multiplying the population number, MSW generation rate, and plastic waste fraction in MSW. Secondly, we entered the number of current waste treatment and disposal, which are divided into plastic waste disposed of in disposal facilities, plastic waste sent to waste-to-energy facilities, plastic waste sorted for recovery from both formal and informal sectors, up to plastic waste in the informal service chain. Moreover, we also predicted the amount of waste managed in controlled facilities judging from level of control [88] of a recovery or disposal facility. To represent the qualitative estimation, We classified the data into low uncertainty, medium certainty, and high uncertainty (see **Appendix Data S3 Table S3**). Low uncertainty is collected directly or gathered from relevant stakeholders, medium uncertainty is the estimation based on concrete data, and high uncertainty is unknown data, which is calculated based on the principle of mass balance.

Data Collection Methods We gained the sources of information in this study from primary and secondary data. Interviews and questionnaires were conducted to the companies, waste generators, waste municipality, governmental institutions, and private sectors by direct encounters or remotely due to the Covid-19 pandemic in the study area. Moreover, field observations were also performed directly or through a remote video call with the on-site team in both cities to reflect the current situation. The observation areas are households, recyclers, waste management infrastructure, and open environment such as land and waterways. Meanwhile, secondary data such as reports, published documents, and websites were gathered from the local authorities, other governmental institutions, and organizations. We used the most updated data into the calculation and obtained the information needed from other reports to create estimations.

Plastic Leakage Identification By using the WFD tool, we could estimate the source and fate of plastic waste leakage [89]. We conducted field observation and interview within both cities to judge the current situation of waste management infrastructure and practices from different stages, which are waste generation, collection, sorting, transportation, and disposal. These judgments were used to input leakage potential level (namely none, low, medium, high, or very high) in the WFD tool (see **Appendix Data S3 Table S4**), in which accompanied with a leakage factor representing the percentage of plastic that could leak into the environment [89]. Furthermore, the fate of plastic waste leakage is assessed into the four destinations (see **Appendix Data S Table S5**), which are burnt, retained on land, storm drains, and waterway [89]. We observed through field observation and interviews within both cities to estimate the amount of plastic waste in the environment for each fate. Further, the material flow used in this study was modified from the results of WFD tool to reflect the presence of non-recyclable plastic in the flow of plastic waste.

Non-Recyclable Plastic Waste Composition Analysis We used a two-step approach to estimate the composition of NRPW in the waterway. Firstly, the amount of plastic waste leakage in the waterway was taken from the results of material flow in Jakarta and Bandung. Secondly, we identified the non-recyclable plastics for both cities based on gathered information from stakeholders and reports findings. From the plastic leakage results of WFD, we distributed the composition of each type of plastic in the waterway leakage using the available report findings, in which the city's waste composition findings for Jakarta and average waste composition findings for Bandung.

# 5.2 *Hotspot and* Leakage Source Mapping

Hotspot identification from population distribution and waste management facilities As non-recyclable plastic waste referred to the unsoundly discarded plastic waste in the environment and low-valued plastics which were unable to proceed further, the sources identified mainly from the waste management facilities and also the residential or settlement categories. This comprehension we applied to define the greater contributor of the plastic leakage. Firstly, to know how low-value plastic waste generated, we used population distribution along 300 m of the riverbank to limit the possibilities of the leakage proximity to the waterway. It also applied to the waste management facilities located in the riverbanks area. We used the buffering and overlay analysis to identify the impacted area in the riverbank and define the distribution along the vulnerable areas thus prone to the discarded material.

Residue calculation as Integration from MFA After the area was identified, each of the point locations is assessed based on the leakage assessment concept on the Waste Flow Diagram tool in Material Flow Analysis methods. The potential zones were assessed using the multi-criteria assessment, where profoundly to the condition of the zone and proximity to the waterway. We divided the condition of the close proximity into 3-potential-zone; low, moderate, and high, where each zone divided respectively per 100 m away from the riverbank area. We conducted the understanding the higher zone had proximity which also implied the deficit of naturalization of the river, where built-up supposedly settled in the river mouth [90] which bring more on plastic waste in the river [91]. The condition of the zone was defined whether the system applied in the area, zonal assessment of slum area based on the economic condition and urban sprawl [48] [92], capacity to retain and manage the waste generated, and assembled systematic schedule.

Vulnerability indexes The distribution of the exact amount of the leakage in the city level based on the material flow analysis was calculated by computing the vulnerability index. Aforementioned multi-criteria assessment, index classified into 3 value divider which 0 as the lowest index value and low probability of leakage, and value 1 is the highest where it also the bigger contributor of the leakage to the waterway. This study mainly focuses on the index on the close proximity and index on the residual–where both main indexes combined to improve the final index of assessment. Index of assessment performed the different value of each zone (facilities and residential area) where we used in the next step as the vulnerability index. Therefore, hotspot was identified by combining both vulnerability index of the waste management facilities and residential area, then we can overlook the potential hotspot in the city level.

## 5.3 Leakage Pathway Modelling

Morphometric Analysis In this study, morphometric analysis has been done to imply the hydrological characterization of the leakage pathway recurring the flash flood. We generated 18 morphometric parameters to deliver the streamflow identification from each watershed towards the peak runoff [71] [93] and implemented the potential capability of each waterway to retain the volume of the water. Focusing on the topographic scale, morphometric parameters were delivered by improvising DEM as the quantitative measurement approach [94]. The elevation model was enhanced and attributed from IFSAR (5 m), TERRASAR-X (5 m), ALOS-PALSAR (11.25 m); which utilizing the high resolution of DEM [95]. As completed with precise DEM; morphometric analysis performed from its scale, topographic, shape and drainage network in metrics [71] [93]; which we performed its impact to approach measurement by weight to emphasize the judgement from scale and topographic as the greater impact [93].

Hydrological Characterization Generalizing the classification of the streamflow, we used the concept of statistical classification method based on the quantification of each major parameter of morphometric parameters. Firstly, we combined the different parameter to each sub-categories (scale, topographic, shape and drainage network) by reclassifying into three-class of response of the peak runoff, whether it is positive or negative correlation [93]. Secondly, we generalized the zonal statistics combination to ensure the judgement of the peak runoff from each sub-category was covered for each whole watershed delineated. In the subsequent, we continued to define the three classes of flow characterization based on the best-fit class distributions. To ease the judgement to the pathway, we divided the flow into high, moderate, low, and unknown; according to the capability of the water retain. Unknown class was identified to improve the unjointed zone from the delineated watershed area based on the well-drainage identification, which prevalent initiated in the coastal area thus Jakarta had the unknown area of watershed.

Calculation of Plastic Waste in the Waterway To comprehend the streamflow and hotspot result, we generated the concept by using proximity analysis for integrating the land-based result to the river pathway [96]. Integration was used by combination of proximity analysis and overlap distribution between the waterway and impacted riverbank of the land-based sources of the leakage. In this case, we improved the distinctive differences summary for numeration of flow classification with the value of the residue. To classify the term, we put a numeration of the plastic material accumulated in the waterway, where low flow has higher accumulation (90% of materials were in the waterway), and high flow has lower accumulation with larger shifting pathway. To distinct the quantification, we assumed based on the composition analysis and the possible occurrences of flash flood [71]. As the condition of higher density than water will sink in the water, we conclude that 50% of materials were retained if the conditions of the flow were high–which quantify the amount of lower accumulation. For moderate flow, we implied 75% materials were accumulated to take the best-fit accordance from low and high class of flow. Therefore, distinct amount of leakage in the waterway defined annually.

Monthly Forecast After the annual accumulation in the pathway has identified, we generated rainfall rate to outline the trend in monthly basis, in term to show how rainfall event affects the possibility of the leakage along with the possible flash flood occurrence and the actual flood historical records [57] [97]. Due to the coverage in the city level, we used the monthly total of rainfall rate based on the satellite [54] [55], which distributed per 11.25 km$^2$. Rainfall rate conducted in mm units, ranged 0 to 900 m depended on the seasons. To conclude the impact of rainfall rate pattern, spatial aspects, and hydrological response; we develop the calculation which shown in the Eq. 1 below.

$$PWL_{Monthly} = \left(\frac{\Sigma PWL}{12}\right) \times \%SP \times \left(\frac{MP}{3}\right) \quad \text{(Eq. 1)}$$

To forecast the distribution of plastic leakage in monthly basis, we developed from the annual accumulation, rainfall contribution, and hydrological response. Where, $\%SP$ quantified based on the rainfall rate distributed each city based on the lowest and peak value. Subsequently, we calculated the weight of each month's rate. Other parameters such as flood historical record was added to the monthly basis of rainfall and quantified as the preset value, which the differences were identified by implied the closest actual conditions. Rainfall data validated and verified by the station recorded [56], where Jakarta covered by two meteorological stations and Bandung with 1 station. The validation across the monthly basis rainfall rate amplified similarity pattern (see **Appendix Data S2**).

## Declarations

**Data Availability**

Data of this study can be accessed through https://figshare.com/articles/journal_contribution/Non-Recyclable_Plastic_Waste_Leakage/19672704 which contains of the result and GIS format.

### Author Contributions

Rinasti, A.N. and Ibrahim, I.F. designed and constructed the overall study; Rinasti, A.N. and Ibrahim, I.F. performed the formal analysis; Rinasti, A.N. conceived the construction of the modelling; Rinasti, A.N. and Ibrahim, I.F. completed the field survey; Rinasti A.N., Ibrahim, I.F., Gunasekara, K., Koottatep, T., and Winijkul, E. wrote the original draft; Gunasekara, K., Koottatep, T., and Winijkul, E. reviewed the original draft. All authors have read and agreed to the published version of the manuscript.

### Competing Interests

All other authors declare no competing interesting.

### Supplementary Information

Supplementary Materials are available in the separate pdf file.

## References

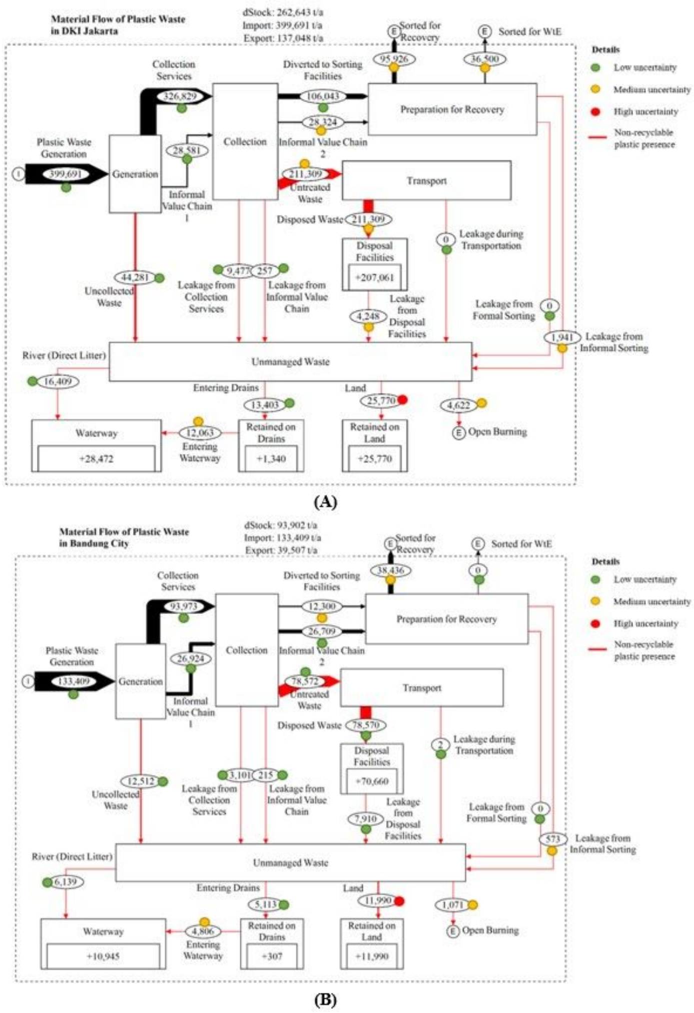
1. Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. Science Advances **3**, 25–29. https://doi.org/10.1126/sciadv.1700782
2. Hopewell, J., Dvorak, R., & Kosior, E. (2009). Plastic recycling: challenges and opportunities. Philosophical Transactions of the Royal Society B: Biological Sciences **364**, 2115–2126. https://doi.org/10.1098/rstb.2008.0311
3. Grigore, M. E. (2017). Methods of recycling, properties, and applications of recycled thermoplastic polymers. Recycling
4. Tanzi, M. C., Fare, S., & Candiani, G. (2019). Chapter 1 - Organization, structure, and properties of materials. Foundations of Biomaterials Engineering, 3–103. https://doi.org/10.1016/B978-0-08-101034-1.00001-3
5. Niaounakis, M. (2017). *Management of marine plastic debris: Prevention, recycling, and waste management.* William Andrew.
6. Central Pollution Control Board. (2018). *Guidelines for the Disposal of Non-recyclable Fraction.* Ministry of Environment, Forest and Climate Change, Government of India.
7. Milios, L., Christense, L. H., McKinnon, D., & Christensen, C. (2018). Plastic recycling in the Nordics: A value chain market analysis. Waste Management, 76, 180–189. https://doi.org/10.1016/j.wasman.2018.03.034
8. Lebreton, L. C. M., Van Der Zwet, J., Damsteeg, J. W., Slat, B., Andrady, A., & Reisser, J. (2017). River plastic emissions to the world's oceans. Nature Communications **8**, 1–10. https://doi.org/10.1038/ncomms15611
9. Meijer, L. J. J., van Emmerik, T., van der Ent, R., Schmidt, C., & Lebreton, L. (2021). More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Science Advances **7**, 1–14. https://doi.org/10.1126/sciadv.aaz5803
10. van Emmerik, T., Loozen, M., Van Oeveren, K., Buschman, F., & Prinsen, G. (2019). Riverine plastic emission from Jakarta into the ocean. *Environmental Research Letters* <bi>1</bi>. https://doi.org/10.1088/1748-9326/ab30e8
11. Rinasti, A. N., Sakti, A. D., Agustina, E., & Wikantika, K. (2020). Developing data approaches for accumulation of plastic waste modelling using environment and socio-economic data product. *IOP Conference Series: Earth and Environmental Science* <bi>592</bi>, 1–13 https://doi.org/10.1088/1755-1315/592/1/012013
12. Sakti, A. D., Rinasti, A. N., Agustina, E., Diastomo, H., Muhammad, F., Anna, Z., & Wikantika, K. (2021). Multi-Scenario Model of Plastic Waste Accumulation Potential in Indonesia Using Integrated Remote Sensing, Statistic and Socio-Demographic Data. ISPRS International Journal of Geo-Information **10**, 1–23. https://doi.org/10.3390/ijgi10070481
13. Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R., & Law, K. L. (2015). Plastic waste inputs from land into the ocean. Science **347**, 768–771. https://doi.org/10.1126/science.1260352
14. Lebreton, L., & Andrady, A. (2019). Future scenarios of global plastic waste generation and disposal. Palgrave Communications **5**, 1–11. https://doi.org/10.1057/s41599-018-0212-7
15. van Emmerik, T., Strady, E., Kieu-Le, T. C., Nguyen, L., & Gratiot, N. (2019a). Seasonality of riverine macroplastic transport. Scientific Reports **9**, 1–9. https://doi.org/10.1038/s41598-019-50096-1
16. van Emmerik, T., Kieu-Le, T. C., Loozen, M., Oeveren, K. van, Strady, E., Bui, X. T., Egger, M., Gasperi, J., Lebreton, L., Nguyen, P. D., Schwarz, A., Slat, B., & Tassin, B. (2018). A methodology to characterize riverine macroplastic emission into the ocean. Frontiers in Marine Science, *5*(OCT), 1–11. https://doi.org/10.3389/fmars.2018.00372
17. Moy, K., Neilson, B., Chung, A., Meadows, A., Castrence, M., Ambagis, S., & Davidson, K. (2018). Mapping coastal marine debris using aerial imagery and spatial analysis. Marine Pollution Bulletin **132**, 52–59. https://doi.org/10.1016/j.marpolbul.2017.11.045
18. Geraeds, M., van Emmerik, T., de Vries, R., & bin Ab Razak, M. S. (2019). Riverine plastic litter monitoring using Unmanned Aerial Vehicles (UAVs). *Remote Sensing* <bi>11</bi>, 6–8. https://doi.org/10.3390/rs11172045
19. Biermann, L., Clewley, D., Martinez-Vicente, V., & Topouzelis, K. (2020). Finding Plastic Patches in Coastal Waters using Optical Satellite Data. Scientific Reports, *10*(1). https://doi.org/10.1038/s41598-020-62298-z

20. Page, R., Lavender, S., Thomas, D., Berry, K., Stevens, S., Haq, M., Udugbezi, E., Fowler, G., Best, J., & Brockie, I. (2020). Identification of tyre and plastic waste from combined copernicus sentinel-1 and-2 data. Remote Sensing **12**, 1–14. https://doi.org/10.3390/rs12172824
21. Themistocleous, K., Papoutsa, C., Michaelides, S., & Hadjimitsis, D. (2020). Investigating detection of floating plastic litter from space using sentinel-2 imagery. Remote Sensing **12**. https://doi.org/10.3390/RS12162648
22. Topouzelis, K., Papageorgiou, D., Suaria, G., & Aliani, S. (2021). Floating marine litter detection algorithms and techniques using optical remote sensing data: A review. Marine Pollution Bulletin **170**, 112675. https://doi.org/10.1016/j.marpolbul.2021.112675
23. Mushtaq, J., Dar, A. Q., & Ahsan, N. (2020). Spatial–temporal variations and forecasting analysis of municipal solid waste in the mountainous city of north-western Himalayas. SN Applied Sciences, *2*(7), 1–18. https://doi.org/10.1007/s42452-020-2975-x
24. Ogwuche, J. A. (2013). Spatial Location of Solid Waste Dumpsites and Collection Scheduling Using the Geographic Information Systems in Bauchi Metropolis, Nigeria. European Scientific Journal **9**, 374–382.
25. Presidential Decree No.97/2017. (2017). National Waste Management Policy and Strategy.
26. Presidential Decree No.83/2018. (2018). Marine Debris Management.
27. Global Plastic Action Partnership. (2020). Radically Reducing Plastic Pollution in Indonesia: A Multistakeholder Action Plan National Plastic Action Partnership [Insight Report]. Geneva: World Economic Forum. https://globalplasticaction.org/wp-content/uploads/NPAP-Indonesia-Multistakeholder-Action-Plan_April-2020.pdf
28. Barrett, A. (2020, May 11). *Why ineffective recycling in Indonesia?* [Webpage Article] https://bioplasticsnews.com/2020/05/11/recycling-problems-indonesia/
29. Ministry of Environment and Forestry (2020): National Plastic Waste Reduction Strategic Actions for Indonesia, Republic of Indonesia
30. Ministry of Public Works and Housing. (2018). Kementerian PUPR Terapkan Teknologi Aspal Plastik dan Aspal Karet Dalam Pemeliharaan Jalan Nasional [Web portal] https://pu.go.id/berita/kementerian-pupr-terapkan-teknologi-aspal-plastik-dan-aspal-karet-dalam-pemeliharaan-jalan-nasional
31. Plastic Waste Management Institute. (2019). *An introduction to plastic recycling.* Plastic Waste Management Institute. https://www.pwmi.or.jp/ei/plastic_recycling_2019.pdf
32. Padeyanda, Y., Jang, Y. C., Ko, Y., & Yi, S. (2016). Evaluation of environmental impacts of food waste management by material flow analysis (MFA) and life cycle assessment (LCA). Journal of Material Cycles and Waste Management **18**, 493–508. https://doi.org/10.1007/s10163-016-0510-3
33. Popoola, A. A., Ayangbile, O. A., & Adeleye, B. M. (2016). Assessment of Solid Waste Management Systems in Ibadan North, Oyo State using Geo-spatial Techniques. Ethiopian Journal of Environmental Studies and Management **9**, 666–679.
34. Cheela, V. R. S., & Dubey, B. (2019). Water Resources and Environmental Engineering II. In Water Resources and Environmental Engineering II. Springer Singapore. https://doi.org/10.1007/978-981-13-2038-5
35. Jakarta Central Bureau of Statistics. (2021). Hasil Sensus Penduduk 2020 Provinsi DKI Jakarta. Jakarta: Jakarta Central Bureau of Statistics. [Webpage] https://jakarta.bps.go.id/pressrelease/2021/01/22/541/jumlah-penduduk-hasil-sp2020 provinsi -dki-jakarta-sebesar-10-56-juta-jiwa.html
36. Jakarta Environment Agency. (2021). Pengelolaan Sampah di DKI Jakarta [document]. Jakarta: Jakarta Environment Agency.
37. Jakarta Government (2019). Kajian Teknis dan Hukum Revisi Peraturan Daerah Provinsi DKI Jakarta Nomor 03/2013 [Document]. Jakarta: Jakarta Government.
38. Bandung Environment Agency. (2019). Neraca Massa Persampahan Bandung November 2020 [Data Tabulation]. Bandung: Bandung Environment Agency.
39. Widyatmoko, H., Sintorini, M. M., Suswantoro, E., Sinaga, E., & Aliyah, N. (2021). Potential of refused derived fuel in Jakarta. *IOP Conference Series: Earth and Environmental Science*, *737*(1). https://doi.org/10.1088/1755-1315/737/1/012005
40. Hidayat, H., Aisyah, S., Rahmadya, A., Husrin, S., Hermana, I. S., Hurley, R., & Olsen, M. (2022). Quantification of Riverbank Macroplastic Contamination in The Lower Citarum River. *IOP Conference Series: Earth and Environmental Science*, *950*(1), 012010. https://doi.org/10.1088/1755-1315/950/1/012010
41. IUCN. (2021). Marine Plastic Pollution [Webpage]. https://www.iucn.org/resources/issues-briefs/marine-plastic-pollution
42. Sukwika, T., dan Noviana, L. (2020). Status Keberlanjutan Pengelolaan Sampah Terpadu di TPST-Bantargebang Bekasi: Menggunakan Rapfish dengan R Statistik. *Jurnal Ilmu Lingkungan Universitas Dipenogoro*, 18(1), 107-118, https://doi.org/10.14710/jil.18.1.107-118
43. Shuker, I. G., & Cadman, C. A. (2018). The Indonesia marine debris hotspot rapid assessment. In The World Bank (Issue April). http://documents.worldbank.org/curated/en/983771527663689822/Indonesia-Marine-debris-hotspot-rapid-assessment-synthesis-report
44. Rakhmawati, A. P., Soemitro, R. A., & Warmadewanthi, I. D. A. (2017). Waste Management Analysis at Tps 3R Mandiri Sejahtera Singosari Malang. *IPTEK Journal of Proceedings Series*, <bi>0</bi>, 65.
45. Khair, H. (2019). Study on waste bank activities in Indonesia towards sustainable municipal solid waste management. (Doctoral disertation, The University of Kitakyushu). https://kitakyu.repo.nii.ac.jp/index.php?action=pages_view_main&active_action=repository_action_common_download&item_id=714&item_no=1&attribute_id=20&file_no=1&page_i=13&block_id
46. Kementrian Lingkungan Hidup dan Kehutanan Republik Indonesia (KLHK). (2021). Sistem Informasi Pengelolaan Sampah Nasional [Webpage]. https://sipsn.menlhk.go.id/sipsn/
47. Muelchi, R., Rössler, O., Schwanbeck, J., Weingartner, R., & Martius, O. (2021). River runoff in Switzerland in a changing climate-runoff regime changes and their time of emergence. Hydrology and Earth System Sciences, *25*(6), 3071–3086. https://doi.org/10.5194/hess-25-3071-2021
48. Lechthaler, S., Waldschläger, K., Stauch, G., & Schüttrumpf, H. (2020). The way of macroplastic through the environment. In *Environments - MDPI* (Vol. 7, Issue 10, pp. 1–30). MDPI AG. https://doi.org/10.3390/environments7100073

49. Haque, M. N., Islam, M. R., & bin Ansar, S. (2018). Assessing the Water Supply, Sanitation and Waste Dumping Condition of Urban Slum: A GIS Based Approach. In *The Jahangirnagar Review, Part II: Social Sciences: Vol. XLII*.
50. Ferronato, N., & Torretta, V. (2019). Waste mismanagement in developing countries: A review of global issues. International Journal Environmental Research and Public Health, 16, 1–28.
51. Ardiansyah, Damar, A., Hariyadi, S., & Machfud. (2022). Current Source and Distribution Pattern of Plastic Waste Leakage in the Estuary of Jakarta Bay. *IOP Conference Series: Earth and Environmental Science*, *950*(1), 012057. https://doi.org/10.1088/1755-1315/950/1/012057
52. Verster, C., & Bouwman, H. (2020). Land-based sources and pathways of marine plastics in a South African context. In *South African Journal of Science* (Vol. 116, Issues 5–6). Academy of Science of South Africa. https://doi.org/10.17159/sajs.2020/7700
53. Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes. Scientific Data, 2, 1–21.
54. Climate Hazards Center UC Santa Barbara. (2021). CHIRPS: Rainfall Estimates from Rain Gauge and Satellite Observations [Web map portal]. https://www.chc.ucsb.edu/data/chirps
55. Meteorology, Climatology, and Geophysical Agency (BMKG) Indonesia. (2021). Pusat Database BMKG [Web portal] https://dataonline.bmkg.go.id/home
56. Bureau of Regional Disaster Mitigation (BPBD) Jakarta. (2021). [Map server] https://jakartasatu.jakarta.go.id/server/rest/services
57. Cordova, M. R., & Nurhati, I. S. (2019). Major sources and monthly variations in the release of land-derived marine debris from the Greater Jakarta area, Indonesia. Scientific Reports 9, 1–8.
58. Haryono, N. A., Untarini, N. (2018). Pelatihan Produk Daur Ulang Sampah Plastik. Dedication: Jurnal Pengabdian Masyarakat, *Maret 2018, 2(1)*, 27–40.
59. Ariyani, D., Warastuti, N., & Arini, R. (2021). Ecobrick Method To Reduce Plastic Waste In Tanjung Mekar Village, Karawang Regency. Civil and Environmental Science, *004*(01), 022–029. https://doi.org/10.21776/ub.civense.2021.00401.3
60. Gumulya, D. (2021). Eksplorasi material daur ulang kantong plastikdengan teknik origami. *Productum: Jurnal Desain Produk (Pengetahuan dan Perancangan Produk), 4*(1), *Januari-Juni 2021*, 15–24.
61. Pasande, P., & Tari, E. (2020). Daur Ulang Sampah di Desa Paisbuloli Sulawesi Tenggara. Dinamisia: Jurnal Pengabdian Kepada Masyarakat, *5*(1). https://doi.org/10.31849/dinamisia.v5i1.4380
62. Muhashiby, M. I. N., Hasibuan, H. S., & Wahyono, S. (2021). Waste Management in Jakarta Recycle Centre: Case Study of Pesanggrahan, Jakarta. *IOP Conference Series: Earth and Environmental Science*, *940*(1), 012034. https://doi.org/10.1088/1755-1315/940/1/012034
63. Kedzierski, M., Frère, D., le Maguer, G., & Bruzaud, S. (2020). Why is there plastic packaging in the natural environment? Understanding the roots of our individual plastic waste management behaviours. Science of The Total Environment, *740*, 139985. https://doi.org/10.1016/J.SCITOTENV.2020.139985
64. Fok L., Cheng I.N.Y., Yeung Y.Y. (2019) Mismanaged Plastic Waste: Far Side of the Moon. In: So W., Chow C., Lee J. (eds) Environmental Sustainability and Education for Waste Management. Education for Sustainability. Springer, Singapore. https://doi.org/10.1007/978-981-13-9173-6_5
65. Sundqvist-Andberg, H., & Åkerman, M. (2021). Sustainability governance and contested plastic food packaging – An integrative review. Journal of Cleaner Production, *306*, 127111. https://doi.org/10.1016/J.JCLEPRO.2021.127111
66. World Bank. (2021). Plastic Waste Discharges from Rivers and Coastlines in Indonesia. Marine Plastics Series, East Asia and Pacific Region. Washington DC.
67. Beck, H. E., van Dijk, A. I. J. M., Miralles, D. G., de Jeu, R. A. M., Bruijnzeel, L. A., McVicar, T. R., & Schellekens, J. (2013). Global patterns in base flow index and recession based on streamflow observations from 3394 catchments. Water Resources Research, *49*(12), 7843–7863. https://doi.org/10.1002/2013WR013918
68. Barbarossa, V.; Huijbregts, M.A.J.; Beusen, A.H.W.; Beck, H.E.; King, H.; Schipper, A.M. FLO1K, global maps of mean, maximum, and minimum annual streamflow at 1km resolution from 1960 through 2015. Sci. Data 2017, 5, 180052. Available online: https://figshare.com/articles/dataset/FLO1K_-_Maximum_Annual_Flow_Time_Series_1960-2015/5688919
69. Lin, P., Pan, M., Beck, H. E., Yang, Y., Yamazaki, D., Frasson, R., David, C. H., Durand, M., Pavelsky, T. M., Allen, G. H., Gleason, C. J., & Wood, E. F. (2019). Global Reconstruction of Naturalized River Flows at 2.94 Million Reaches. Water Resources Research, *55*(8), 6499–6516. https://doi.org/10.1029/2019WR025287
70. Adnan, M. S. G., Dewan, A., Zannat, K. E., & Abdullah, A. Y. M. (2019). The use of watershed geomorphic data in flash flood susceptibility zoning: a case study of the Karnaphuli and Sangu River basins of Bangladesh. Natural Hazards **99**, 425–448. https://doi.org/10.1007/s11069-019-03749-3
71. National Oceanic and Atmospheric Administration (NOAA). (2022). Flood and Flash Flood Definitions [Web portal] https://www.weather.gov/mrx/flood_and_flash
72. Tambunan, M. P. (2017). The pattern of spatial flood disaster region in DKI Jakarta. *IOP Conference Series: Earth and Environmental Science*, *56*(1). https://doi.org/10.1088/1755-1315/56/1/012014
73. Nuryanto, D. E., Pawitan, H., Hidayat, R., & Aldrian, E. (2021). The occurrence of the typical mesoscale convective system with a flood-producing storm in the wet season over the Greater Jakarta area. Dynamics of Atmospheres and Oceans, *96*, 101246. https://doi.org/10.1016/J.DYNATMOCE.2021.101246
74. Water Resources Service Jakarta (DSDA). (2021). Pantau Banjir Jakarta [Web portal] https://pantaubanjir.jakarta.go.id/
75. Priyambodoho, B. A., Kure, S., Yagi, R., & Januriyadi, N. F. (2021). Flood inundation simulations based on GSMaP satellite rainfall data in Jakarta, Indonesia. Progress in Earth and Planetary Science, *8*(1). https://doi.org/10.1186/s40645-021-00425-8
76. Tjia, J. A. L. (2021). *Assessing the impact of plastic waste accumulation on nood events with citizen observations A case study in Kumasi, Ghana*. http://repository.tudelft.nl/.

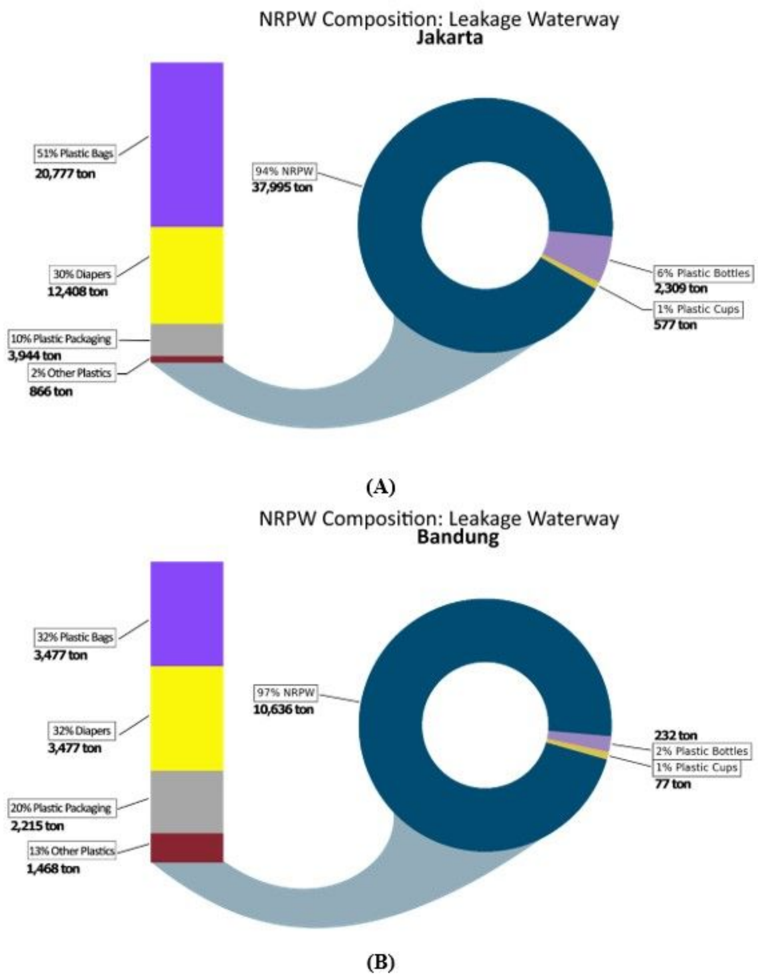
77. Uijttewaal, Wim; Honingh, Dorien Frederique ; Kardhana, Hadi ; Hoes, Olivier ; van de Giesen, Nick. / The effects of plastics in riverine waste on accumulation at a debris rack. E-proceedings of the 38th IAHR World Congress. Panama City, 2019. https://research.tudelft.nl/en/publications/the-effects-of-plastics-in-riverine-waste-on-accumulation-at-a-de
78. Honingh, D., van Emmerik, T., Uijttewaal, W., Kardhana, H., Hoes, O., & van de Giesen, N. (2020). Urban River Water Level Increase Through Plastic Waste Accumulation at a Rack Structure. Frontiers in Earth Science, *8*(February), 1–8. https://doi.org/10.3389/feart.2020.00028
79. Ragaert, K., Huysveld, S., Vyncke, G., Hubo, S., Veelaert, L., Dewulf, J., & du Bois, E. (2020). Design from recycling: A complex mixed plastic waste case study. Resources, Conservation and Recycling, *155*, 104646. https://doi.org/10.1016/J.RESCONREC.2019.104646
80. Visvanathan, C. (2020, November). *Design for recycling and role of EPR in plastic recycling* (Lecture notes, Circular economy for plastic waste management, Marine Plastics Abatement, School of Environment, Research and Development). Pathum Thani: Asian Institute of Technology.
81. Klemeš, J. J., Fan, Y. van, Tan, R. R., & Jiang, P. (2020). Minimising the present and future plastic waste, energy and environmental footprints related to COVID-19. Renewable and Sustainable Energy Reviews, *127*, 109883. https://doi.org/10.1016/J.RSER.2020.109883
82. Widiati, S. (2020). Rebricks: From Plastic Waste to Eco-friendly Bricks Rebricks: From Plastic Waste to Eco-friendly Bricks [Web article] https://nowjakarta.co.id/people/community/rebricks-from-plastic-waste-to-eco-friendly-bricks
83. Nursyamsi, N., Indrawan, I., & Theresa, V. (2018). Effect of HDPE plastic waste towards batako properties. *IOP Conference Series: Materials Science and Engineering*, *309*(1). https://doi.org/10.1088/1757-899X/309/1/012013
84. Darmawan, L. (2020). Pertama di Indonesia, Sampah RDF Jadi Pengganti Batu Bara [Web article] https://www.mongabay.co.id/2020/07/27/pertama-di-indonesia-sampah-rdf-jadi-pengganti-batu-bara/
85. Jakarta Central Bureau of Statistics. (2021). DKI Jakarta Province in Figures. Jakarta: Jakarta Central Bureau of Statistics.
86. Bandung Central Bureau of Statistics. (2020) Bandung city in Figures. Bandung: Bandung Central Bureau of Statistics. https://bandungkota.bps.go.id/publication/2020/04/27/0a1cfa49906db067b3fb7e5e/kota-bandung-dalam-angka-2020.html
87. UN-Habitat. (2020). Waste Wise Cities Tool: SDG 11.6.1. A step-by-step guide for a rapid assessment of SWM systems in cities. [Webpage] https://unhabitat.org/waste-wise-cities-campaign
88. Cottom, J., Zabaleta, I., Zurbruegg, C., Stretz, J., & Eschborn, B. S. (2020). User manual: Waste flow diagram (WFD): A rapid assessment tool for mapping waste flows and quantifying plastic leakage. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. [Webpage] https://archive.researchdata.leeds.ac.uk/751/1/Waste_Flow_Diagram-User_Manual.pdf
89. Building Design Partnership (BDP). (2019). Jakarta River Development [Webpage] https://www.bdp.com/en/projects/f-l/jakarta-river/
90. Peng, Y., Wu, P., Schartup, A. T., & Zhang, Y. (2021). Plastic waste release caused by COVID-19 and its fate in the global ocean. PNAS, *118*(47), 1–6. https://doi.org/10.1073/pnas.2111530118/-/DCSupplemental.Published
91. Bureau of Research and Development Bandung (Bappelitbang Bandung). (2019). SIKAKU – Basis Data Kawasan Kumuh Kota Bandung [Web Map] https://sikaku.cityplan.id/map.html
92. Abdel-Fattah, M., Saber, M., Kantoush, S. A., Khalil, M. F., Sumi, T., & Sefelnasr, A. M. (2017). A hydrological and geomorphometric approach to understanding the generation of wadi flash floods. Water (Switzerland) **9**, 1–27. https://doi.org/10.3390/w9070553
93. Asfaw, D., & Workineh, G. (2019). Quantitative analysis of morphometry on Ribb and Gumara watersheds: Implications for soil and water conservation. International Soil and Water Conservation Research, 7(2), 150–157.
94. DEMNAS National Mapping Agency Indonesia (DEMNAS BIG). (2021). Seamless Digital Elevation Model (DEM) dan Batimetri Nasional [Web map portal]. https://tanahair.indonesia.go.id/demnas/#/\
95. National Mapping Agency (BIG) Indonesia. (2021). Indonesia Geospatial Portal [Web map portal] https://tanahair.indonesia.go.id/portal-web
96. Bandung Geodata. (2021). Bandung Geodata: Pola Ruang Bandung [Web map portal] http://103.108.201.6/layers/geonode:POLARUANG_AR
97. 97. Bandung Geodata. (2021). Bandung Geodata: Pola Ruang Bandung [Web map portal] http://103.108.201.6/layers/geonode:POLARUANG_AR


## Figures



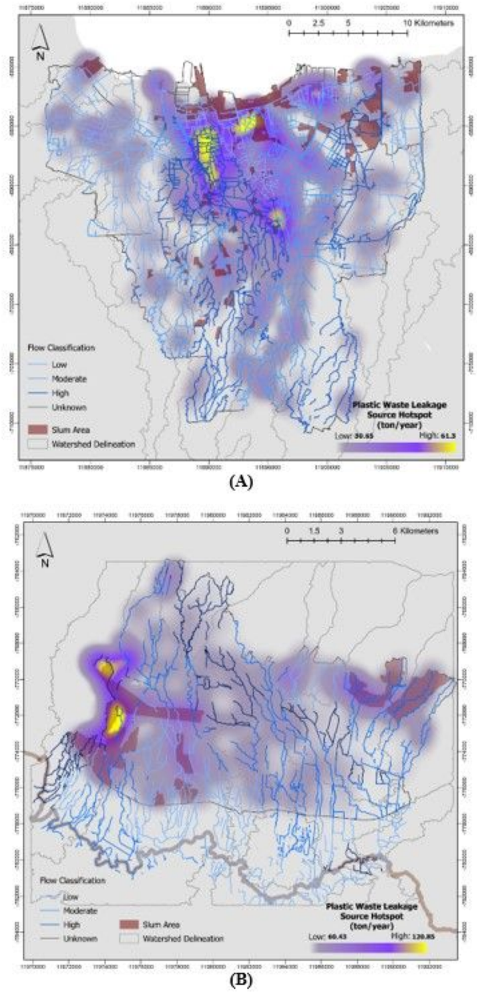

## Figure 1

Material Flow of Plastic Waste **(A)** DKI Jakarta **(B)** Bandung




## Figure 2

Plastic Waste Composition from Waterway **(A)** DKI Jakarta **(B)** Bandung




## Figure 3

Plastic Leakage Pathway Model based on the Hotspot from Treatment Residues **(A)** Jakarta **(B)** Bandung

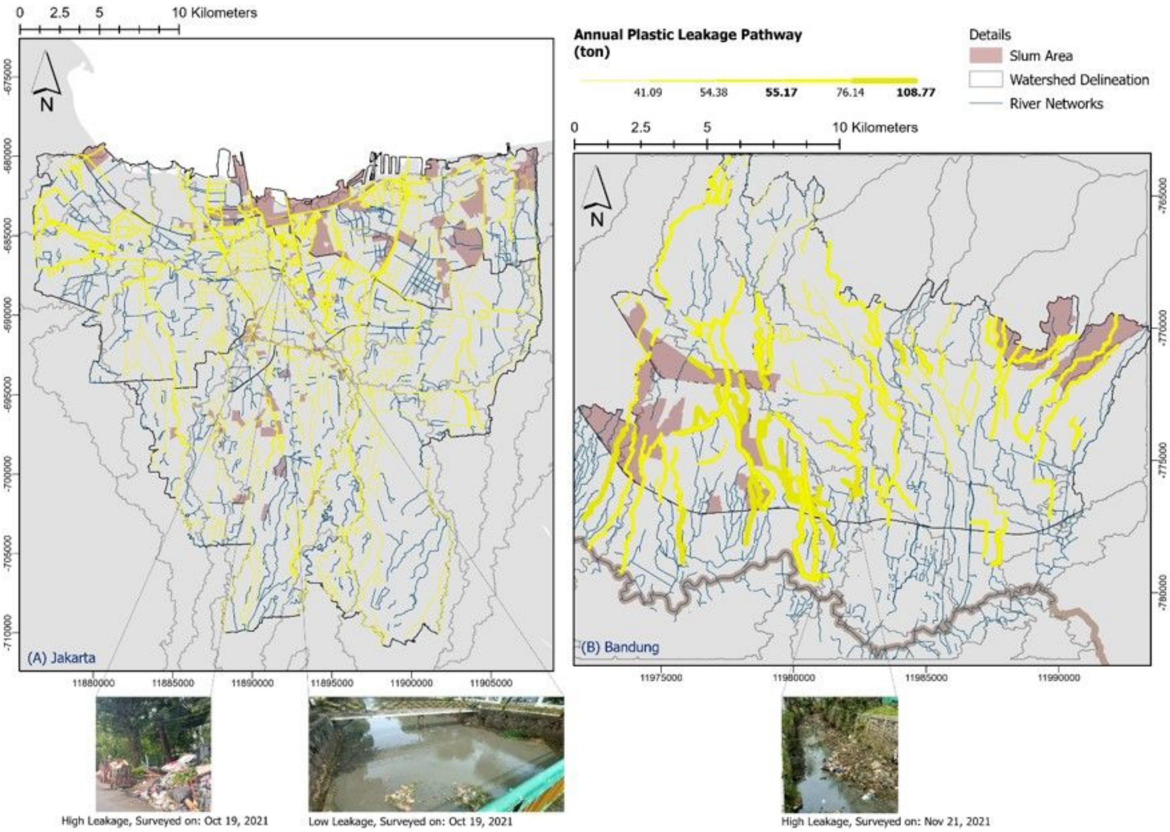



**Figure 4**

Plastic Leakage Pathway Model based on the Accumulation Input to the Waterway

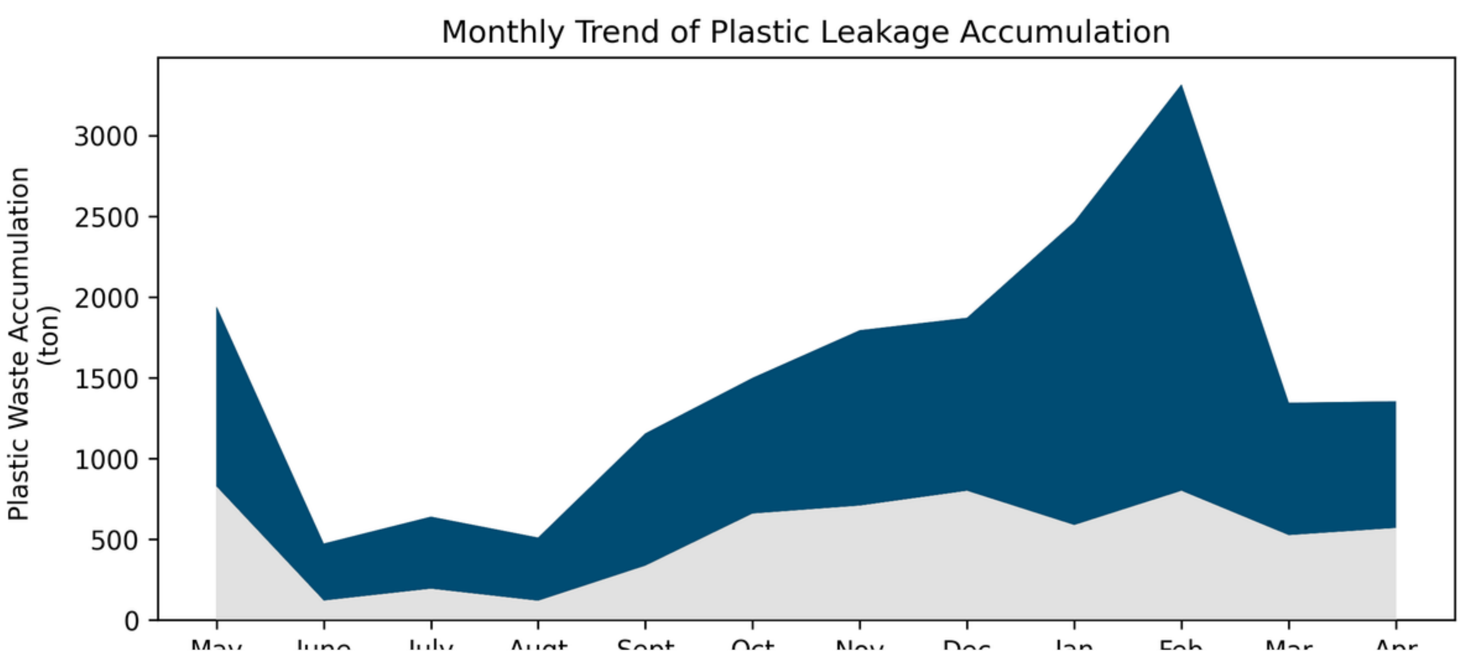



**Figure 5**

Monthly Leakage Accumulation in Two Cities

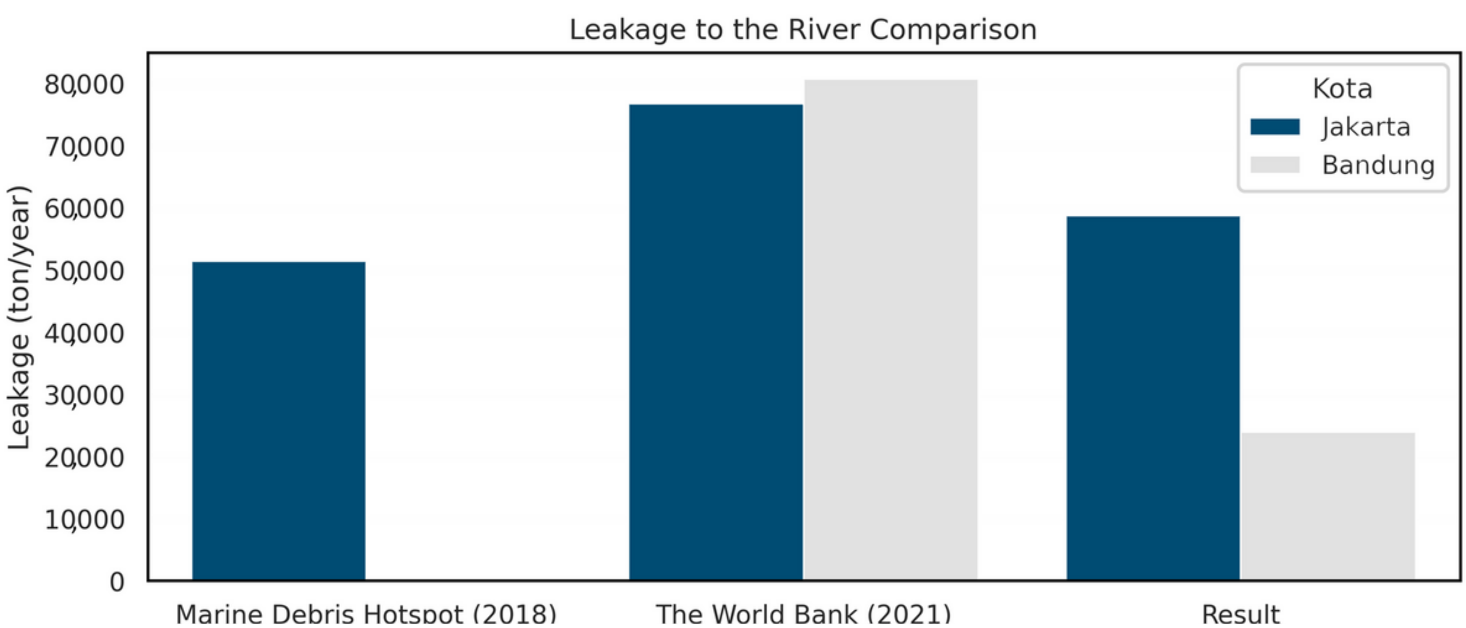



Figure 6

Graphical Comparison of Plastic Leakage to the River Pathway though years

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterials.docx