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Characterization of Transboundary Transfer Mechanisms for Improved Plastic Waste Management: A Study on the U.S.–Mexico Border

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Abstract: The vast majority of ocean plastics originate from land and are transported over long distances to their final sink. Yet, our current understanding of transfer mechanisms through rivers and estuaries remains poor due to a lack of consistent methods for assessing and monitoring plastic waste. In this study, we quantify and characterize the abundance of plastics in the Tijuana River estuary, located along the U.S.–Mexico border. We found a total of 2804 plastic debris items, of which 79.3% were sampled during heavy rainfalls and 20.7% during the dry period. Overall, most plastics were attributed to five economic sectors: packaging, food, construction, fishing, and tourism, highlighting losses during the use and waste management phases of the plastic's value chain. Based on the results of the analysis, consistent monitoring of plastic pollution is recommended for managing variable plastic loads.

Keywords: plastic pollution; Tijuana River; estuary; U.S.–Mexico border; monitoring

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1. Introduction

Over the past century, there has been a striking increase in the occurrence and magnitude of plastic emissions into the world's oceans [1,2]. Nearly 90% of ocean plastics originate from land-based sources and enter the sea mainly from riverine systems [3,4]. Land-based inputs are assumed to be proportional to the mismanagement of plastic waste within a 50 km wide coastal zone [2], but it has been shown that waterways can facilitate the transport of plastic waste over longer distances into the ocean [5]. Thus, scholars have highlighted the need to assess the probability of mismanaged plastic waste reaching rivers and waterways, and then the ocean [6].

A nationwide assessment of mismanaged waste found nearly 26 billion debris items along U.S. waterways with high potential of entering the ocean [7]. Every year, between 0.51 and 1.45 million metric tons of mismanaged plastics end up in coastal waters [8], and the U.S. spends roughly USD 11.5 billion on cleanups and plastic leakage containment [9]. Although the reduction in plastic waste emissions into waterways is high on socio-political agendas [7], consistent assessments are still lacking. Spatial data on mismanaged plastics along the U.S. coastline are limited to concentrated efforts and generally lack a comprehensive national baseline for debris monitoring [10]. This becomes even more problematic along border regions, where inconsistent traceability of plastic flows, substantial differences in material accounting, and poor exchange of information make monitoring pollution transfer patterns a particularly difficult task [11].

Detailed knowledge of riverine influx as part of waste management is required to address currently uncaptured plastic waste streams [4,12]. Yet, our present understanding of transfer mechanisms in rivers and estuaries is insufficient, which leads to an underestimation of global plastic inputs into the ocean [13]. This is mainly due to the lack of extensive, standardized, and systematic monitoring methodologies for riverine influx to allow robust comparison across catchments and material flow assessments of larger regions [3]. Additionally, spatio-temporal variability of plastic dispersal and transport in rivers can significantly vary due to changes in hydrodynamic conditions (including seasonal stream capacity, hydrological cycles, and the occurrence of meteorological events) [14–16], which may affect the accuracy of pollution monitoring protocols [4,5]. These challenges inevitably hamper the development of pollution management and reduction strategies [17,18].

These considerations highlight the need for critical applications of monitoring methodologies to assess variability and dispersal patterns of plastic fluxes within relevant riverine compartments. In this paper, we propose a way to estimate plastic emissions into the sea based on quantification and characterization of plastic loads in the context of the Tijuana River estuary (Imperial Beach, CA, USA), located along the U.S.–Mexico international border. In particular, we aim to (1) characterize the composition and variability of mismanaged plastic waste flows; (2) understand the contribution of the principal economic sectors in plastic pollution; (3) map plastic's transfer mechanisms from source to sink; and (4) deepen our understanding of loopholes in the current waste management infrastructure.

2. Methods

2.1. Study Area

The investigation was carried out in the context of the Tijuana River (193 km), which originates in the Sierra de Juárez (Ensenada, Mexico) and flows across the international border into the U.S., ending in the Pacific Ocean. The river is considered the most polluted waterway in San Diego County (CA, USA), and one of the top five most polluted rivers in California, due to the influx of waste from the neighboring Tijuana region (Mexico) [19,20]. Here, persistence of mismanaged waste can result from (i) lack of debris removal and leakage containment targets; (ii) lack of consistent cleanups and removal efforts; (iii) inefficiency of the existing waste retainment infrastructure, especially due to waste overflowing during wet periods; and (iv) lack of consistent monitoring and waste assessment programs [21–25].

The sampling sites were located across the Tijuana River estuary, located in Imperial Beach (California), which was identified by the authors as one of the hotspots of transboundary plastic pollution along the U.S.–Mexico border. Additionally, estuaries are considered significant corridors for the transport of plastics into the ocean [26], hence the dual value of this location.

2.2. Plastic Debris Sampling Methods

The team for the observer-based survey included two experienced observers, also in charge of recording the information collected, and one assistant. Data were collected in the Tijuana River estuary between the months of February and April 2023, consistently with the occurrence of exceptional storms and rainfalls [27–29]. To assess the impact of meteorological events like rainfall episodes on the plastic loads, we monitored litter during dry and heavy rainfall periods, as advised by Tramoy et al. [15].

Litter surveys were conducted during low tides to increase the survey's rigor and facilitate beach access to the estuary, following the NOAA's guidelines for macro-debris surveys [30]. Upon arrival at the sampling location, the site boundaries were identified and marked using flag markers and ropes, and plastic litter (sized 2.5 cm or larger) was monitored along transects running perpendicular to the course of the river and sized

10 m × 20 m (transect area ~200 mq). Overall, 16 transects were inspected over four sampling sessions, for a plastic debris total of 2804 (Figure 1). For each collected item, the following characteristics were recorded: (1) geographical location; (2) material type (plastic or rubber); (3) item type; (4) polymer type; (5) weight; (6) source; and (7) photographic evidence (recorded with a GoPro 9 Hero with fixed settings, at an altitude of 0.50 m). Data were collected independently by the three surveyors and subsequently combined and cross-compared for accuracy by the two experienced surveyors, also with the help of photographic evidence.

Figure 1. Map of the transects along the Tijuana River estuary, California.

2.3. Characterization of Plastic Mass Flows

Classification and quantification of plastic litter were conducted on site. Count (number of items) and amount (weight in kg) were used to calculate the mass flows of macroplastics. Mass flows were calculated for each transect and period, and classified following the JRC guidelines for macroplastic identification [31]; debris that could not be classified into the proposed classification was listed as "miscellaneous". Only plastic and rubber types of debris were included in this analysis due to their significantly higher abundance compared to other materials.

Identified litter was then divided into land-based sources, including households (e.g., consumer goods, cleaning supplies, beauty and personal products), packaging (e.g., wrappers, shopping bags), food (e.g., cups, tableware), medical (e.g., COVID masks), construction (e.g., pipes, sheeting, tubes), and transportation (e.g., tyres, vehicle parts), and sea-based sources, such as fishing (e.g., fishing lines, ropes), and tourism (e.g., fins, snorkeling masks, beach toys), according to the classification proposed by UNEP [32].

3. Results

3.1. Plastic Mass Flows

A total of 2804 plastic debris items were sorted and counted according to the JRC classification [31] for dry (N = 581, 20.7%) and heavy rainfall (N = 2223, 79.3%) periods, denoting substantial temporal variations in plastic pollution levels measured in the different periods (Figure 2) (see detailed description in Supplementary Materials Table S1). These results confirmed those of previous studies conducted in Southern California that found that plastic loads were higher after a storm compared to dry periods [33–35].

Data collection for the heavy rainfall period was carried out during the months of February and March 2023. Eight transects were sampled and reported a total of 2223 litter items, with a frequency of 310.4 item/transect, and a total weight of 104.5 kg, with an average weight of 14.3 kg/transect. The frequency of litter per transect varied between 50 items on T1 to 451 items on T8, weighing 4.2 kg and 20.4 kg, respectively. This variability in frequency and amount of litter can be attributed to the characteristics of the transects presented in Table 1.

Table 1. Overview of sampling sessions and transect characteristics.

Date	Time	Period	Weather Conditions	Site Description	Transect #	Collected Plastic Items (#)	Amount of Plastic (kg)
26 February 2023	3–5 p.m. PT	Heavy rainfall	54 °F, mostly sunny, wind 7 mph E, humidity 58%	Along shoreline, cleaner	T1	50	4.2
					T2	127	5.9
				When estuary meets salt water	T3	213	10.5
					T4	316	17.4
2 March 2023	2–4 p.m. PT	Heavy rainfall	57 °F, sunny, wind 6 mph NE, humidity 58%	Near wildlife refuge, farther from shoreline	T5	422	19.3
					T6	225	10.3
				At the estuary, more polluted	T7	419	16.5
					T8	451	20.4
5 April 2023	4–6 p.m. PT	Dry	61 °F, sunny, wind 7 mph NW, humidity 54%	Near wildlife refuge, farther from shoreline	T9	51	3.9
					T10	16	3.0
				At the estuary	T11	65	5.9
					T12	33	0.7
11 April 2023	10.30 a.m.–12.30 p.m. PT	Dry	58 °F, partly cloudy, wind 4 mph W, humidity 84%	Along shoreline, waste washed up	T13	83	8.5
					T14	123	12.6
				When estuary meets salt water	T15	132	13.9
					T16	78	5.9

Data collection for the dry period was carried out in April 2023. Eight transects were sampled and reported a total of 581 litter items, with a frequency of 72.6 item/transect, and a total weight of 53.8 kg, with an average weight of 7.7 kg/transect. The frequency of litter per transect varied between 16 items on T10 to 132 items on T15, weighing 3.0 kg and 13.9 kg, as shown in Table 1, respectively.

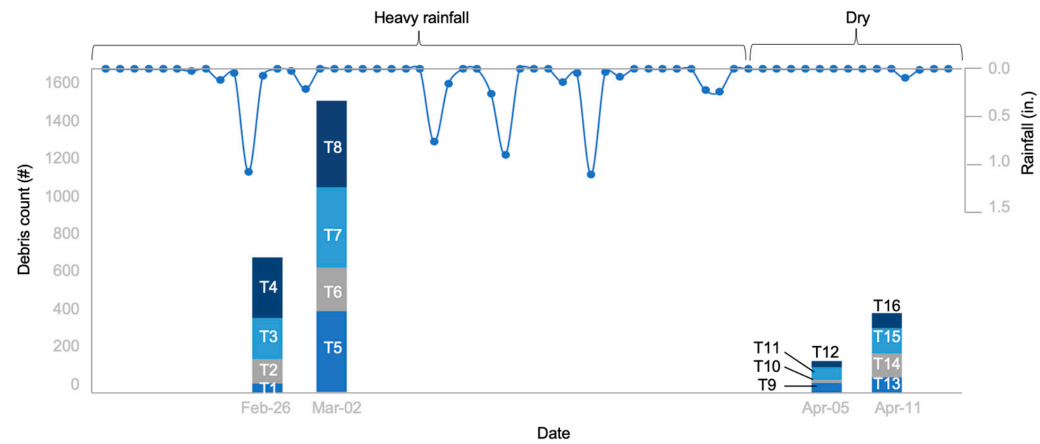

Figure 2. Temporal variation in plastic pollution levels during heavy rainfall and dry periods.

3.2. Plastic Composition

3.2.1. Most Common Plastic Products

For both the heavy rainfall and dry period, we found that miscellaneous plastics (unidentified plastic fragments sized 2.5–5 cm) were the most abundant specific items, with a frequency of encounter of 1175 for the first period and 125 for the latter, in line with the results of similar studies [15,36]. During the heavy rainfall period, the top five frequently found plastic products included (i) plastic caps/lids, (ii) polystyrene pieces, (iii) fishing lines, (iv) tubes, and (v) other wrappers. During the dry period, the top five frequently found plastic products included (i) other wrappers, (ii) plastic caps/lids, (iii) fishing lines, (iv) plastic industrial packaging, and (v) straws, denoting some similarities between the two hydrological periods. The most abundant items (with a frequency of 10 items or more) for the two periods are shown in Figure 3.

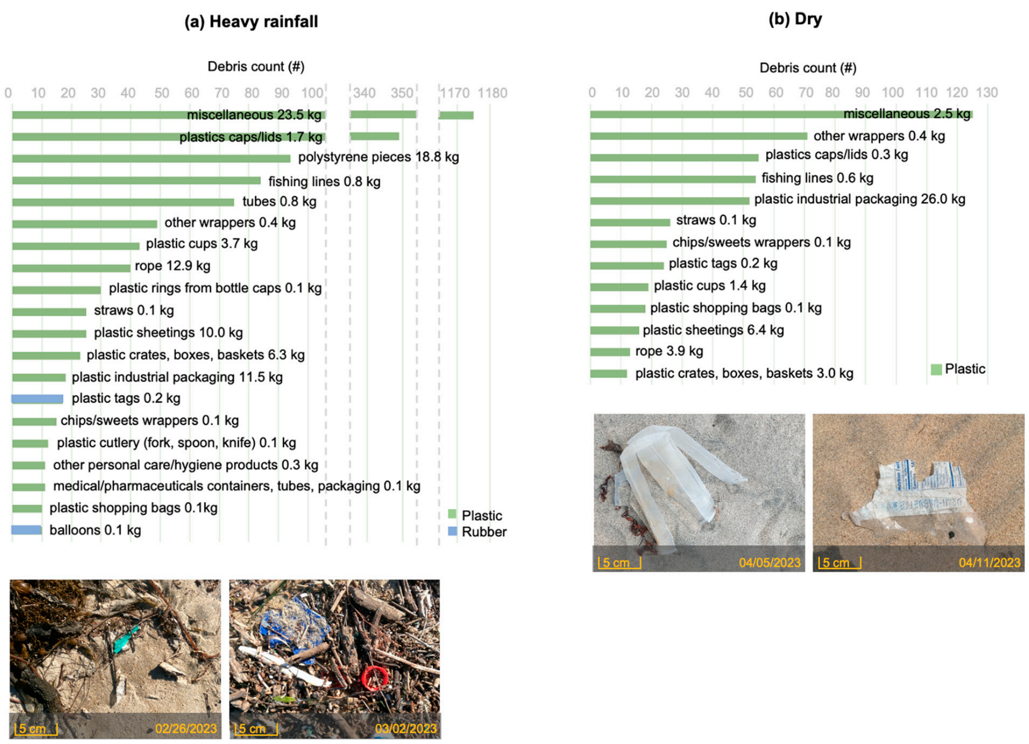

Figure 3. Frequency of most common debris (>10 debris items) collected during heavy rainfall and dry periods.

3.2.2. Polymer Composition

For both the heavy rainfall and dry period, we found that mixed polymers (multi-layer, plasmix, or non-identifiable polymers) were most abundant, constituting more than half (53.6%) of the plastic waste collected during heavy rainfalls, and about one quarter (25.8%) of that collected during the dry period. The analysis of the polymer composition for the heavy rainfall period shows that other common polymers include high-density polyethylene (HDPE) (21.2%) and polypropylene (PP) (7.4%); while other polymer types constituted less than 5% of the total collected debris. The analysis of the polymer composition for the dry period shows that other common polymers include HDPE (24.6%), low-density polyethylene (LDPE) (15.3%), PP (10.3%), nylon (9.3%), and rubber (5.3%); while other polymer types constituted less than 5% of the total collected debris. The results of the polymer composition analysis are illustrated in Figure 4.

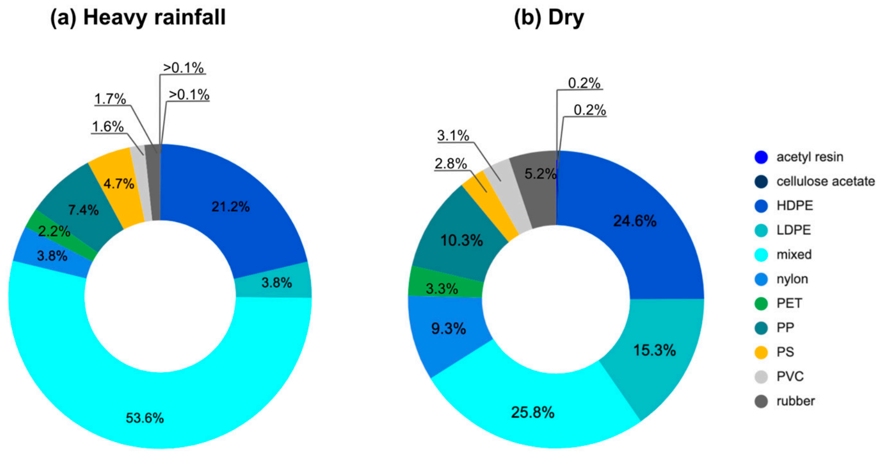

Figure 4. Polymer composition of plastic waste collected during heavy rainfall and dry periods (HDPE: high-density polyethylene; LDPE: low-density polyethylene; PET: polyethylene terephthalate; PP: polypropylene; PS: polystyrene; PVC: polyvinyl chloride).

3.3. Economic Sectors

When possible, we assigned plastic products to their respective sources and economic sectors, as shown in Figure 5. A total of 1300 items were classified as "unidentified plastics/miscellaneous" and hence excluded from this analysis because of their ambivalent nature. Of the remaining 1504 debris, the majority was attributed to land-based sources, comprising 87.3% of plastic litter collected during heavy rainfalls and 84.0% of that collected during the dry period.

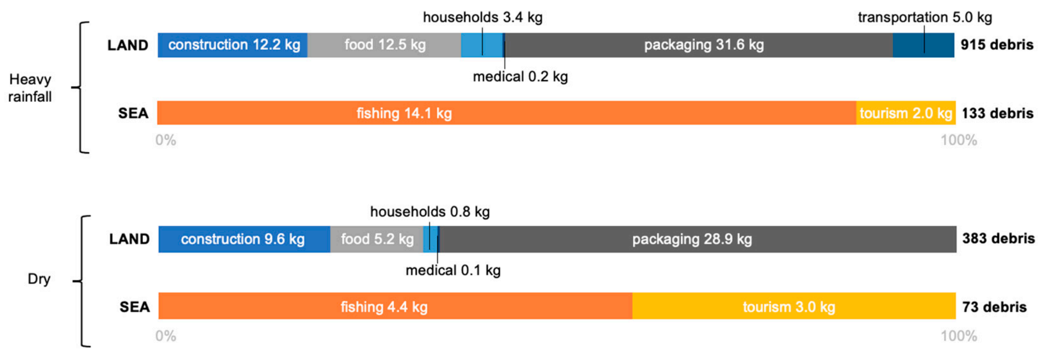

Figure 5. Litter composition by source and economic sector (unidentified fragments are excluded from this categorization).

For all periods, we observed a similar litter composition relative to land-based sources, with packaging being the first economic sector by weight and accounting for 48.7% (31.6 kg) and 64.8% (28.9 kg) of the total identified plastic waste during the heavy rainfall and dry period, respectively. Commonly identified packaging items included wrappers, plastic industrial packaging, and plastic shopping bags. These results resonate with global [37] and national estimates [38,39] on plastic packaging waste, and are in line with previous studies [15].

During heavy rainfalls, food was the second identified economic sector, accounting for 19.3% (12.5 kg) of the identified mismanaged plastics. This sector presented the highest diversity of products, ranging from tableware and related accessories like straws and stirrers, to larger items such as trays and food boxes. Third, the construction sector accounted for 18.8% (12.2 kg) of mismanaged plastics, although it presented a lower diversity of products (plastic and rubber sheeting, and tubes) compared to the other two economic sectors. Finally, plastic waste from transportation, households, and the medical sector constituted each less than 10.0% of the total amount of identified waste.

During the dry period, construction was identified as the second economic sector, accounting for 21.5% (9.6 kg) of identified mismanaged plastics, in the form of sheeting and tubes. Third, the food sector accounted for 11.7% (5.2 kg) of identified mismanaged plastics and presented the highest diversity in terms of collected products (e.g., tableware, food-related accessories, food boxes, etc.). Finally, the household and medical sector each constituted less than 10.0% of the total amount of identified waste.

Similarly, we observed an analogous litter composition relative to sea-based sources. For all periods, the majority of identified ocean plastics was attributed to the fishing industry, which accounted for 84.4% (14.1 kg) of mismanaged plastics during heavy rainfalls and 59.5% (4.4 kg) of mismanaged plastics during the dry period. Commonly identified fishing plastics included fishing lines, ropes, and buckets. These results are consistent with those of previous studies [40,41].

Finally, tourism was the second identified sector for the production of sea-based plastics, accounting for 15.6% (2.0 kg) and 40.5% (3.0 kg) of ocean plastics sampled during the heavy rainfall and dry period, respectively. Primary tourism plastics included snorkeling gears and other accessories associated with coastal tourism activities. In contrast to other sectors, differences in variability of tourism plastics should be attributed to the seasonality of coastal tourism activities. Therefore, it is not surprising that we observed a higher density of tourism plastics during the dry season.

3.4. Fate and Transport of Plastic Debris

In our previous study [42], we found that the vast majority of plastic entering the Pacific Ocean through the Tijuana River estuary originates in Tijuana (Mexico), where persistent littering, lack of formal waste collection systems, proximity to informal housing, and spread of unauthorized dumping sites have made the river a convenient dumpsite over the years and a primary corridor of plastic pollution into the U.S. side of the Tijuana River Watershed. This fate might be extended to most land-based plastics sampled in the estuary. Material losses can occur at different stages of the value chain from plastic use to waste disposal; from there, they can be released into waterways and coastal waters through direct deposit, uncollected waste, inadequate disposal, or abandonment and loss of plastic materials (Figure 6). For both hydrological periods, land-based plastics identified in this analysis were attributed to three primary economic sectors: packaging (e.g., plastic shopping bags, wrappers, industrial plastic packaging), food (e.g., tableware, cups, food trays and containers), and construction (e.g., plastic sheeting and tubes). In addition to land-based plastics, we found a number of sea-based plastics from fishing (e.g., fishing lines and ropes) and tourism-related activities (e.g., snorkeling equipment).

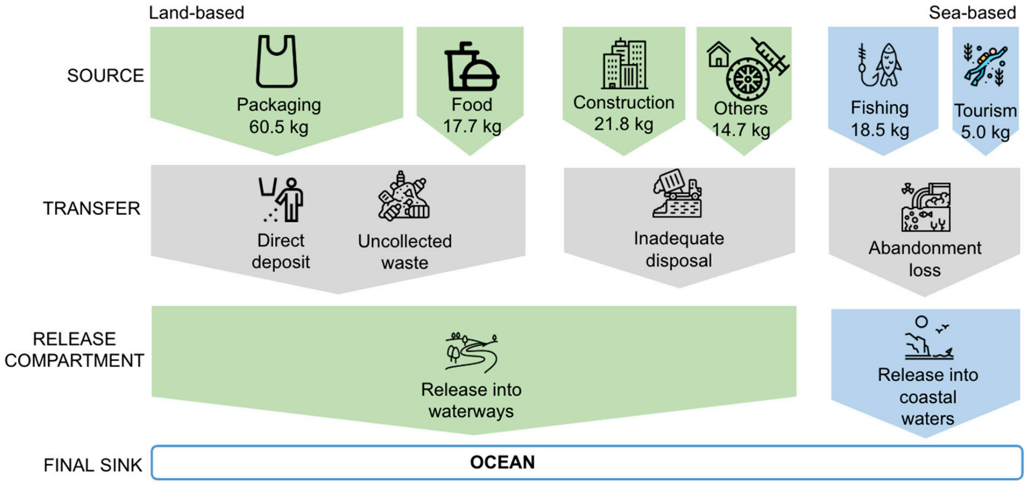

Figure 6. Sources, fate, and transport of marine litter identified in the Tijuana River estuary.

4. Discussion

4.1. Implications for Research and Practice

This research enriches our current understanding of transboundary plastics along international borders, which are often overlooked in both local and global plastic pollution assessments. This is the third study monitoring plastic pollution fluxes from Mexico into the U.S. in the context of the Tijuana River estuary (Imperial Beach, California). However, the other two studies—the Southern California Coastal Water Research Project and the monitoring program of the Tijuana River National Estuarine Research Reserve [25]—are limited in scope and scale, and thus not suitable for providing comprehensive monitoring of riverine influx. The present study characterizes the movement of transboundary plastics by assessing and quantifying plastic variability and composition, primary sources, and pollution pathways, hence contributing to the following areas of research and practice.

From a scientific perspective, the study demonstrates the value of adopting an integrated monitoring methodology to supplement the current lack of spatially explicit data (reviewed by [43,44]) on magnitude, distribution, and temporal variability of plastic pollution, their sources, fate, and pathways from land to sea. On one hand, the multi-level, multi-method approach enabled us to capture a more comprehensive dataset of observations to provide a systemic assessment and characterization of mismanaged plastic waste flows, which, in turn, allowed us to identify the most vulnerable areas of the socio-technical system that require priority interventions to control and mitigate material losses into the environment. On the other hand, it addresses the existing difficulties (portrayed by [45]) in connecting pollution generating sectors and activities (e.g., fishing, offshore mining, maritime transport, tourism, illegal dumping, transport, etc.) to their contributions to plastic pollution.

From a managerial perspective, our study introduced a temporal perspective in plastic pollution monitoring that provides implications for assessing and managing variable plastic loads. Our results showed higher concentrations of plastic pollution during heavy rainfalls than dry periods, suggesting that hydrological characteristics have a direct impact on plastic loads (see also [15,33–35]). Finally, another managerial contribution of this study lies in the characterization of the primary sources and transport patterns of transboundary plastics. Packaging, construction, and food were identified as the top three sectors associated with land-based pollution, while sea-based pollution was primarily attributed to fishing and tourism. From there, plastic debris can reach the sea via intentional or unintentional loss and mismanagement of plastic waste post-consumption. The results of this analysis provide industrial stakeholders with a more detailed understanding of current mismanaged plastic flows. This enables us to guide and implement ad hoc guidelines and recommendations on how to manage such plastic flows through, for example, waste prevention, containment, and recovery strategies towards plastic circularity.

4.2. The Role of Pollution Monitoring in End-of-Life Management

In this paper, we illustrate how monitoring riverine influx can help: (1) identify the loopholes in existing value chains and waste management systems; (2) deliver up-to-date comprehensive data on the composition of mismanaged plastic waste streams; (3) define needs and priorities along the value chain to guide policies; and (4) provide science-based guidelines for the plastic industry, waste management sector, and sea-based economic activities to track and manage leakages and pollution flows, and mitigate their impacts on the marine environment (Table 2).

Table 2. Open challenges and opportunities from pollution monitoring.

Decisional Areas	Identification of Loopholes in the Plastic Cycle	Improving Data Collection on Mismanaged Plastic Flows	Definition of Needs and Priorities to Guide Policies	Providing Science-Based Industrial Recommendations for Managing Plastic Flows
Open challenges	-Presence of unidentified debris. -Uncertainty about geographical/economic sources. -Lack of understanding of pathways and means of release.	-Lack of plastic losses/mismanagement estimates. -Limited knowledge of spatio-temporal variability of plastic loads.	-Localized and fragmented policy response. -Limited focus and coverage of leakage reduction policies. -Uneven policy implementation.	-Industry fragmentation. -Lack of systemic coordination. -Lack of informed design.
Opportunities from pollution monitoring	-Mapping loopholes in value chain and waste management systems. -Identification of problems and critical spatial areas. -Variability of waste streams and uncaptured flows. -Geo-spatial distribution of polluting actors/activities.	-Classification of debris' physical–morphological characteristics. -Increasing technological capacity by overcoming the limits of single technologies. -Providing cross-national data collection.	-Definition of indicators and standards for comprehensive pollution assessment. -Informed leakage control interventions. -Informed industry-level measures. -Policy impact assessment.	-Identification of plastic leakages/loopholes, high-risk areas. -Enabling conditions for a system change and informed collaborations.
Case study application	-Identification of land- and sea-based sources. -Losses during use and waste disposal phases. -Pollution release into waterways and coastal waters.	-Most abundant plastic items: packaging plastics, plastic components from construction sector, fishing gears, and tourism plastics.	-Issues with existing local response and cleanup interventions. -Need for upstream-to-downstream monitoring of the plastic's value chain to support informed policies.	-Need for interventions to the waste management infrastructure. -Need for upstream measures to reduce plastic loss and abandonment.

Pollution monitoring allowed us to identify the spatio-temporal variability of trans-boundary plastics (Section 3.1), composition (Section 3.2), primary geographical and economic sources (Section 3.3), and fate and transport patterns (Section 3.4). Monitoring plastic losses along the value chain allowed us to define functions and industrial actors that most heavily contribute to plastic pollution and hence require priority action [46]. It is in fact critical to monitor upstream stages of the plastic's value chain (e.g., production and use) that bear impacts on downstream stages (e.g., end-of-life and waste management), in line with the findings of [47].

In our analysis, we found that greatest plastic losses occur at two stages of the plastic's value chain: the use stage and waste management. Our analysis showed that between 80 and 90% of identified plastics originated from land-based sources; from there, losses can occur during the use stage as a result of littering and intentional or unintentional abandonment into waterways and coastal waters, and eventually enter the ocean. Losses can also result from improper waste management including inadequate disposal and uncollected waste in the proximity of waterways, where mismanaged waste is more at risk of ending up in water bodies.

Concerning plastic's production and use, we found that land-based plastics mainly originate from three economic sectors, packaging, food, and construction, while sea-based plastics come from fishing and tourism activities. In general, marine litter management strategies at these stages include reduction in plastic consumption, substitution of plastics with alternative materials, and implementation of extended producer responsibility (EPR) programs [12,46]. In particular, detailed knowledge of the waste material streams and most abundant plastic items is useful for upstream industrial actors to concentrate waste reduction efforts at the source and implement measures targeting the products that are more likely to be improperly disposed of.

Secondly, similar to other studies conducted at the global level [12], losses result from inadequate waste management and call for an improvement of the waste collection and management infrastructure as a direct means to reduce plastic losses. At the international level, cross-border solutions are imperative to effectively manage plastic waste streams on both sides of the international border. Suggested options include (but are not limited to) standardization of waste collection and treatment targets between San Diego and Tijuana, ban of illegal dumping sites along the Tijuana River, maintenance and improvement of existing waste-retainment systems located across the Tijuana River Watershed.

At the local level, pollution monitoring enables us to identify the areas that require priority intervention as well as the main issues with existing waste management activities, including formal and informal beach cleanups. A more detailed understanding of these challenges is critical to guide and design policies to meet the specific needs and implement tailored regulatory instruments [48].

Finally, at the industrial level, effective interventions can include (i) closing the leakage points within the collection and waste management infrastructure to eliminate inadequate disposal, accidental losses, and mismanagement of plastic waste near waterways; (ii) expanding plastic waste collection to reduce the probability of leakage into water bodies; and (iii) combining a variety of end-of-life management technologies to recover and treat plastic waste [49].

This holistic systemic understanding of plastic losses throughout the entire plastic's life cycle can support meaningful mitigation and leakage control strategies, as effective management of plastic pollution requires combined efforts at all stages of the value chain [50].

5. Conclusions

To the best of our knowledge, this is the second study assessing plastic pollution in Imperial Beach, California. While the first study [19] investigated the quantity and distribution of plastic debris on the Imperial Beach shoreline, the present work concentrated on the movement and variability of transboundary plastics in the Tijuana River estuary by assessing plastic loads, material types, and sources of plastic pollution.

Some limitations of the present study are related to the dataset used. In fact, extending the sampling periods to capture a greater variety of weather and hydrological conditions could enable a better understanding of the specific variables affecting variability of plastic loads. Second, the high presence of unidentified plastics necessitates further analysis (e.g., laboratory, microscopic, spectrometric analysis) to identify respective material composition and sources. Third, sampling different segments along the river would allow us to map transfer mechanisms across a larger region and estimate how much plastic eventually reaches the ocean. Finally, future research could include the assessment of micro- and nanoplastics by sampling sand sediments and releasing these into the water column to yield a more accurate assessment of plastic loads entering the ocean.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/w17121819/s1, Table S1: Transect analysis for heavy rainfall and dry periods.

Author Contributions: Conceptualization, C.M. and P.T.; methodology, C.M., D.V. and G.F.; formal analysis, C.M.; writing—original draft preparation, C.M.; writing—review and editing, C.M. and P.T.; visualization, C.M.; supervision, P.T. All authors have read and agreed to the published version of the manuscript.

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