Earth's Future

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Key Points:
- We developed a holistic model of riverine macroplastic and debris sources, sinks and transport dynamics for urban rivers
- Much more debris is directly deposited on the floodplain by dumping and abandoned homeless encampments, than is washed in through stormwater
- Despite clean-up efforts, and some emission to the ocean, increasing quantities of debris are accumulated in the river corridor over time

Supporting Information:
Supporting Information may be found in the online version of this article.

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Quantifying Sources, Sinks and Mitigation of Macroplastic and Other River Debris: A Trash Balance Model

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Abstract Mismanaged consumer plastics and other waste that enters a river system, known as riverine debris, is a pervasive problem in urban rivers with consequences for ecosystem health and human livelihood. A better understanding of the loading pathways, fluxes, and fate of this debris is necessary for more effective mitigation efforts, and to reduce ocean emissions that become marine debris. This study presents a novel framework for quantifying riverine debris using a holistic mass balance modeling approach, applied in the San Diego River, California, a regionally important river with a large, urban watershed. This framework quantifies urban riverine debris sources, sinks and transport dynamics at the watershed scale. The model integrates a community science data set of floodplain debris with a simple stormwater runoff model to account for debris loading and applies probabilistic transport functions to estimate ocean emissions. Our key finding is that most riverine debris in the San Diego River is not washed in through storm drains but is directly deposited in the floodplain (79%–92% of total debris), with homeless encampments the largest contributing factor (62%–75% of total debris). Ongoing cleanup efforts substantially reduce the debris accumulation rate: without these efforts, debris stored on the floodplain increases by up to 48%. However, despite cleanups debris continues to accumulate over time with the potential for increased ocean emissions in subsequent years, especially during years with large flood events. Our approach is transferable to other urban rivers to understand the fate and flux of local debris, and therefore to inform effective mitigation initiatives.

Plain Language Summary Mismanaged consumer plastics and other waste that enters a river system, known as riverine debris, is harmful to ecosystems, and damages human livelihoods. Effectively reducing riverine debris requires an understanding of the origin, movement, and fate of debris at a watershed scale. This paper introduces a new comprehensive model of riverine debris, demonstrated in an urban river in Southern California, using community-based surveys and field experiments to estimate sources and fate of debris. Model results show that most riverine debris is directly deposited into the floodplain by dumping and abandoned homeless encampments, while debris washed into the river from surrounding areas is a lesser concern. Our study location showed increasing quantities of debris input and stored in the river corridor over the period 2019–2023, despite clean-up efforts, which leads to more debris being washed out to the ocean when flooding occurs.

1. Introduction

Global consumer waste production and the prevalence of waste in the environment continues to increase, despite improvements in waste management practices and technologies (Borrelle et al., 2020; Hoornweg et al., 2013; Jambeck et al., 2015). As a result, consumer waste, a large portion of which is environmentally persistent plastics, is now ubiquitous in urban rivers (Lau et al., 2020; Morales-Caselles et al., 2021). Such riverine debris (defined here as all mismanaged consumer waste in rivers, river margin and floodplain areas) endangers aquatic species, causes economic harm, can exacerbate urban flooding, and has potential impacts to human health (Honingh et al., 2020; Lechthaler et al., 2020; Leslie et al., 2022). Rivers are appreciable debris sinks that accumulate waste over time (Kooi et al., 2018; van Emmerik et al., 2022). Accumulated debris items break down into micro debris and microplastics, which then cause harm as they are readily ingested by biota including species consumed by humans (Wang et al., 2017). Indeed, macro-plastic is the largest source of secondary microplastic in rivers (Horton & Dixon, 2017; Hurley et al., 2020). Not only does debris damage the local riverine environment, a portion is transported downstream and is a known major source of marine debris (Meijer et al., 2021; van

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Emmerik et al., 2023). Total global plastic debris inputs from rivers into the sea are estimated to be between 1.15 and 2.41 million tons (Lebreton et al., 2017; Schmidt et al., 2017).

As awareness of the problem of riverine debris has increased, so too have cleanup and mitigation efforts (United Nations, 2018). For example, the California Trash Amendments mandates inlet filters to reduce storm drain sourced debris by 2030 and aims to reduce riverine debris, as many storm drain outfalls terminate in urban rivers (California Environmental Protection Agency, 2015). Yet, in many urban rivers direct dumping in floodplains and along river margins is well documented and may represent a greater source of riverine debris than indirect stormwater debris (Rech et al., 2015; van Emmerik & Schwarz, 2020; Williams & Simmons, 1999). This may be especially true in urban catchments where illegal dumping or homeless encampments are prevalent (Flanigan & Welsh, 2020; White, 2013). Many materials typical of homeless encampments such as plastic, polystyrene and manufactured wood fall under the category of macro, persistently buoyant items that are the dominant source of marine debris exported from rivers (Rech et al., 2014; van Emmerik, Strady, et al., 2019). For example, the Rhone river exports more than 200,000 such items per year to the ocean (Castro- Jiménez et al., 2019). In these urban rivers, removal of debris from the floodplain may be necessary for successful mitigation (McCormick & Hoellein, 2016). To determine effective mitigation strategies, we therefore require a holistic understanding of the major sources, sinks and transport pathways of debris in urban rivers.

Previous authors have proposed integrated mass balance models to simulate urban riverine debris but such an approach has yet to be implemented or applied to individual rivers of concern (Hoellein & Rochman, 2021; Liro et al., 2020; van Emmerik & Schwarz, 2020). Instead, many studies focus on a single aspect of the riverine debris budget. Examples include surface microplastic or macroplastic concentrations (Cowger et al., 2022; Islam et al., 2022), macroplastic transport distances (Duncan et al., 2020; Lotcheris et al., 2024), riverbank trash (Hoellein et al., 2014; Poletti & Landberg, 2021), or microplastics in river sediments (Klein et al., 2015). Other studies measure numbers of debris items or fragments but lack mass estimates (Xiong et al., 2019). Recent global probabilistic riverine debris emissions models have been informed by empirical investigations (Jambeck et al., 2015; Lebreton et al., 2017; Meijer et al., 2021). However, these models do not distinguish loading pathways, which is necessary to inform and improve local mitigation efforts. Urban debris includes a mix of debris types, yet most previous river transport studies focus on macro- and micro-plastic (Lechner et al., 2014; Schmidt et al., 2017), with less attention paid to non-plastic or mixed-material debris.

In this study, we therefore develop and implement a holistic mass balance model of debris transport into and through an urban river. This “trash balance” model provides a comprehensive accounting of riverine debris at the watershed scale, enabling the user to identify the major sources of debris, to evaluate the effectiveness of potential mitigation strategies, and to estimate emissions to the ocean. We implement the model in the lower San Diego River, an urban river typical of Southern California in its ongoing challenges with debris and homelessness (Figure 1). Community-based surveys and cleanup efforts in the lower San Diego River show large quantities of riverine debris, much of which can be attributed to abandoned homeless encampments in the floodplain (SDRPF, 2020). Our model incorporates locally available data on debris presence and transport, an existing community science riverine debris data set (SDRPF, 2024) and a locally calibrated stormwater debris runoff model (Bagheri et al., 2024).

Our objectives are to develop a framework for a watershed-scale mass balance model of riverine debris, and implement the model using local data sources for a case study watershed. We aim to assess mobilization and transport of debris stored in the floodplain, which is typically inundated by the 1- to 2-year storm event; flow from smaller storms will typically remain below the bankfull stage and will only mobilize debris deposited directly in the river channel. We use the model to analyze the magnitude of different sources of debris into the river channel, identify effective mitigation strategies, assess trends in the quantity of debris stored in the river margins, and quantify the mass of debris exported to the ocean.

2. Study Area: Lower San Diego River, Southern California

The urban lower reach of the San Diego River drains a watershed of area 419 km^2. The San Diego River is a regionally important river that drains to recreational beaches, with a large urban watershed. In San Diego Bay, the total debris exceeds 20.4 million plastic pieces (SD Bay Debris Study Workgroup, 2016). Two reservoirs intercept all runoff from the sparsely populated upper watershed. Approximately 520,000 people reside in the entire San Diego River watershed according to 2010 census data, the vast majority in the Lower San Diego River.

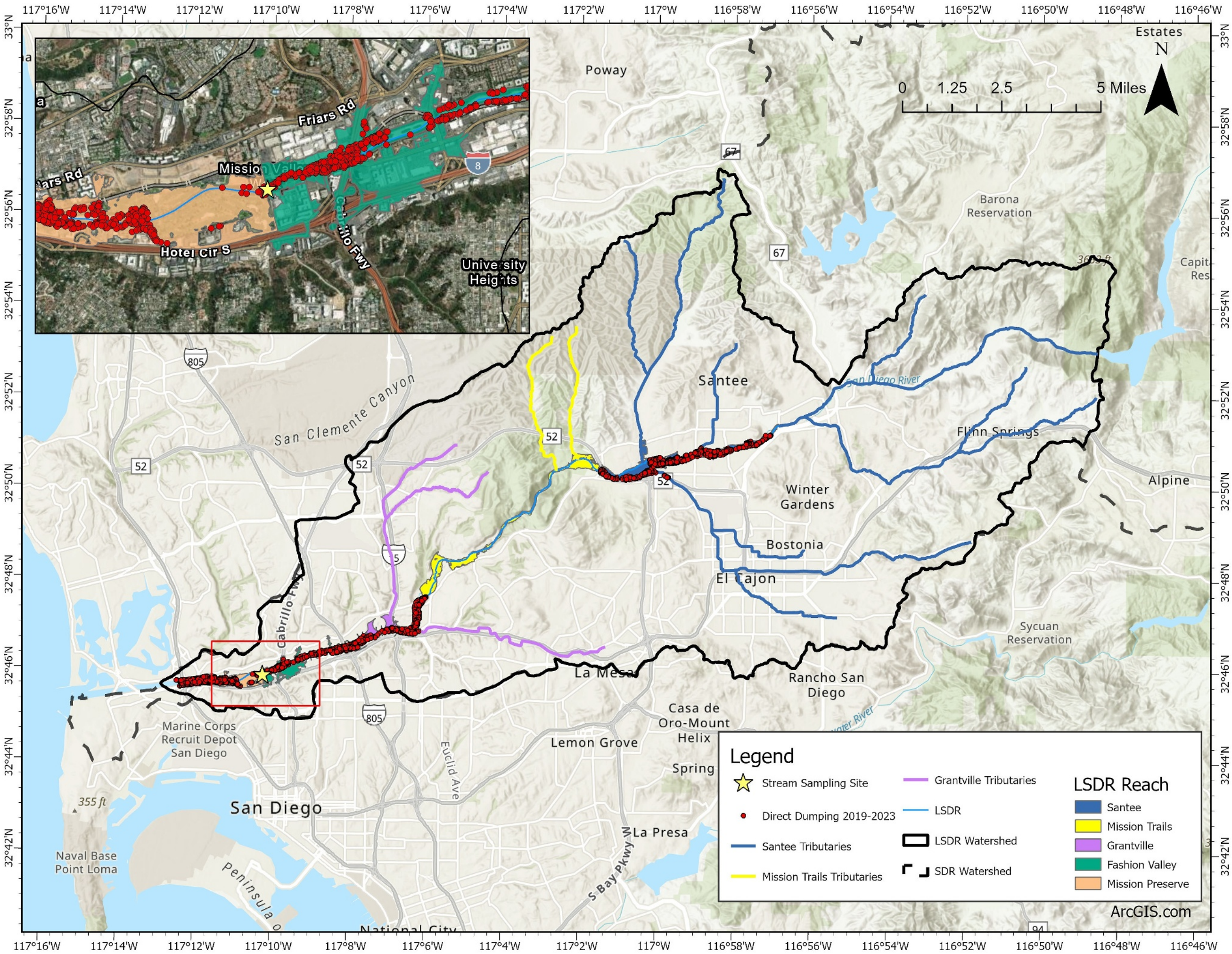

Figure 1. Lower San Diego River (LSDR) watershed with Reaches 1–5, upstream to downstream; Santee, Mission Trails, Grantville, Fashion Valley, and Mission Preserve. Each colored reach polygon is the 500-year recurrence interval floodplain of that river section. Surveyed debris outside this margin is not considered in our model. Stream sampling site location indicated by gold star is 200 m downstream of USGS gauge 11023000. Inset; Fashion Valley reach with river margin direct debris dumping sites for all water years.

The Lower San Diego River watershed has four main land use types: 31% residential, 2.5% industrial, 56.5% open space, and 10% commercial (Bagheri et al., 2024). The mainstem is a non-channelized perennial river with extensive riparian vegetation cover. Summer flows are persistent but generally low (1–2 m^3s^{-1}) and winter flows are flashy, with a 2-year recurrence interval flow of 57.5 m^3s^{-1} (USGS, 2023). The Köppen climate classification for San Diego is hot-summer Mediterranean (Csa), with hot dry summers and cool wet winters. Rainfall is concentrated in a few storms each year, and 90% of precipitation falls from November to April (Ahn et al., 2005). Despite a low average annual rainfall of 270 mm (Isla et al., 2004), daily rainfall is highly variable and flood risk is substantial, particularly during atmospheric river events that can cause rainfall in excess of 70 mm/day (Dettinger et al., 2011). This pattern of events exacerbates water quality impacts and debris transport, because usually dry areas of the floodplain provide large areas that accommodate a sizable homeless population, but are occasionally swept by flood waters.

We delineate the Lower San Diego River into 5 distinct reaches: Santee (R1), Mission Trails (R2), Grantville (R3), Fashion Valley (R4), and Mission Preserve (R5). Each reach has distinct land use characteristics, jurisdiction, or is bounded by open space (e.g., golf course, natural park). We use these distinct reaches to represent spatial variability in model inputs and parameters (Figure 1).

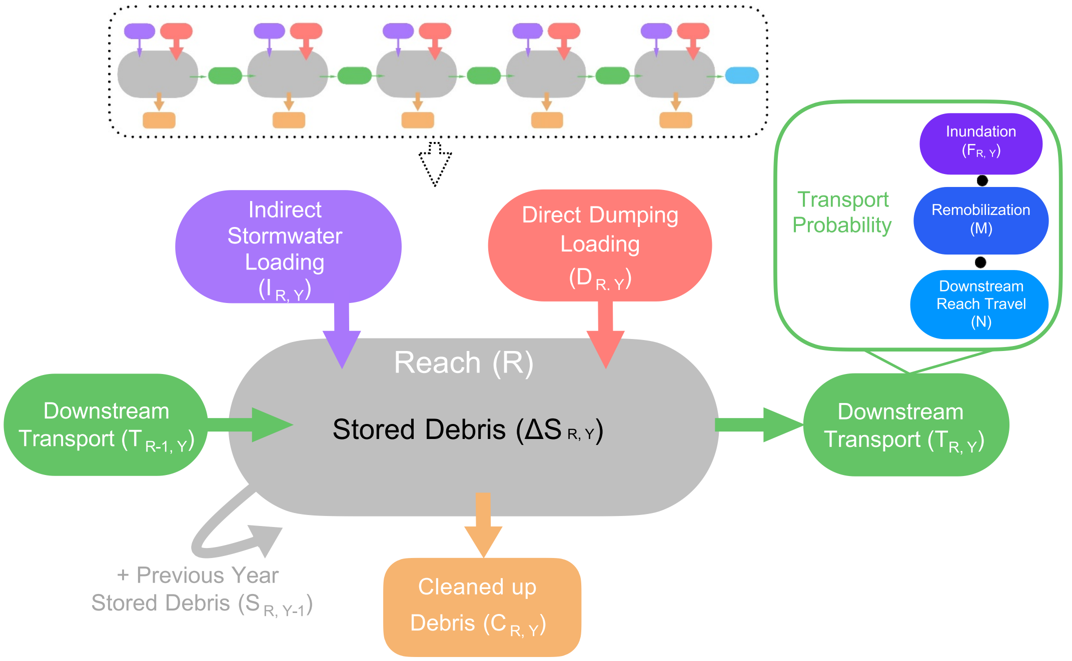

Figure 2. Schematic of the watershed scale trash balance model at top and detail of the loading sources, stores, transport and output fluxes for a single reach.

3. Methods

3.1. Model Overview

We developed a novel riverine debris model based on the conceptual structure proposed by Liro et al. (2020) to simulate macroplastic storage and remobilization in rivers. The model distinguishes human and environmental controls of riverine debris loading and outputs, and includes remobilization, transport, and storage mechanisms (Figure 2). The model can be used to predict debris output to the ocean, and to analyze the magnitude and trends of debris stores and fluxes in the river corridor.

The model uses an annual water year timestep to accommodate data on debris loading rates and river corridor storage quantities that are often only available on an annual basis. Spatial discretization is based on user-defined river reaches. The model has two main spatial units: the river corridor (including the river, its margins, and the floodplain), and the entire river watershed that drains to the river corridor via storm drains or tributaries to the mainstem.

The model state equation for riverine debris volume in an individual reach of the river corridor is given in Equation 1.

$$S_{R,Y} = S_{R,Y-1} + I_{R,Y} + D_{R,Y} + T_{R-1,Y} - C_{R,Y} - T_{R,Y} \quad (1)$$

Terms are defined as follows, all with units of mass. Subscript R indicates the river reach, and Y the water year. Stored debris $S_{R,Y}$ represents debris stored at the end of the water year for each reach. The model includes two debris sources: indirect stormwater debris ($I_{\mathrm{R,Y}}$), which represents debris transported from the watersheds that drain to the main river corridor by stormwater runoff and wind, and direct debris dumping in the river corridor ($D_{R,Y}$), which includes littering, illegal dumping and debris from abandoned homeless encampments in the river corridor. Debris transport from the adjacent upstream reach ($T_{R-1,Y}$) is a loading term to a given reach but is not an additional source. The model has two output pathways: the intentional removal of debris through cleanup efforts ($C_{\mathrm{R,Y}}$), and downstream transport in the river ($T_{\mathrm{R,Y}}$).

Downstream transport $T_{R,Y}$ is modeled as follows:

$$T_{R,Y} = S_{R,Y} \cdot F_{R,Y} \cdot M \cdot N \tag{2}$$

Where $F_{R,Y}$ is the fraction of stored debris in reach R of the river corridor that is inundated during the annual maximum flood in year Y, M is the probability that an inundated debris item is remobilized, and N is the probability that a remobilized debris item will travel to the adjacent downstream reach. Probabilities F, M, and N are unitless. For the upstream-most reach, $T_{0,Y}$ is zero (representing the limits of the urban area), and for the downstream-most reach, $T_{R,Y}$ represents debris emission to the ocean at the river outlet.

The model has simplifying assumptions. We assume that the annual maximum discharge is the primary control on the annual transport of debris in the river corridor. This assumption is supported by the manyfold increase in debris concentration and deposition during extreme discharge events (van Emmerik et al., 2023), but may underrepresent transport by smaller events. Field observations (Section 3.4) suggest that debris transport is very small during events that do not inundate the floodplain. The model assumes all stored riverine debris is equally subject to downstream transport, whether accumulated during prior years or the current year, and does not account for likely differences in mobilization probabilities of surface debris versus debris buried in sediment. The model assumes that debris can travel at most one reach downstream per year. By using these simplifying assumptions, the model structure provides first estimates of loading, downstream transport and ocean emissions.

The following sections describe how each model term was estimated for the Lower San Diego River site.

3.2. Model Variables and Parameters

The variables and parameters of the model were determined from a combination of modeling, community science, field observations, and existing literature. Briefly, a regional stormwater debris loading model (Bagheri et al., 2024) was used to estimate indirect stormwater debris I (Section 3.2.1). A community science data set provided estimates of direct dumping D (Section 3.2.2) and clean-up C (Section 3.2.3) (SDRPF, 2024). Inundation probabilities $F_{R,Y}$ were estimated from a discharge time series and flood inundation maps overlaid on maps of debris accumulation (Section 3.2.4). Field experiments were conducted to estimate remobilization probabilities M (Section 3.2.5). Estimates of downstream transport probability N were taken from the literature (Section 3.2.6). The model was initialized for the period of modern plastic use (Section 3.3) and validated using measurements of debris loads collected near the outlet during storm events from September 2022 to March 2023 (Section 3.4).

3.2.1. Indirect Stormwater Loading (I)

Indirect Stormwater Loading represents debris that is washed into the river corridor by stormwater runoff from the surrounding watershed. A regional stormwater simulation model, SWMM (Huber, 1985), was adapted to estimate this debris source (Bagheri et al., 2024). This method for quantifying indirect riverine debris loading is broadly applicable to any urban watershed. The SWMM model uses urban debris buildup and washoff rate parameters derived from a Los Angeles County Baseline Study, which installed over 500 full capture debris devices in storm drains in the Los Angeles River and Ballona Creek Watersheds from 2002 to 2004 (County of Los Angeles Department of Public Works Watershed Management Division, 2004). Buildup rate (mass per area) is the quantity of debris that builds up during dry periods and washoff rate (mass per time) is the quantity of debris that is subsequently washed into the river during a rain event. Each capture device drained one land use type allowing for land use specific buildup and washoff parameters. Buildup and washoff parameters were then calibrated to match debris generation rates from a similar debris capture study in San Diego County, though not all observations were in the Lower San Diego River watershed (Michael Baker International, 2018). Mean annual water year washoff load, the relevant measure for this study, was a function of antecedent dry days, runoff rate (mm hr^{-1}), watershed area, land use type, and the locally calibrated debris buildup and washoff parameters. Washoff load was assigned to the appropriate Lower San Diego River reach based on watershed outlines in the SWMM model. As none of the capture devices in the local study were in open space, and it is assumed that undeveloped open space contributes negligible debris with very little if any foot traffic, this land use type is assumed to contribute runoff but no debris. Urban parks, which do have significant foot traffic and debris deposition, were approximated as commercial land use type although there may be differences in stormwater infrastructure and washoff rate. To account for uncertainty in washoff load an additional set of debris washoff rates from the Ballona Creek watershed were considered, representing a feasible maximum water year washoff load for the Lower San Diego River (Supplementary Table 1 in Supporting Information S1).

3.2.2. Direct Debris Dumping (D)

Direct dumping represents debris entering the river corridor due to littering, illegal dumping and debris from abandoned homeless encampments. This quantity is estimated for the Lower San Diego River using a data set provided by the San Diego River Park Foundation (SDRPF), which has surveyed river floodplain debris since 2018, with over 80 annual surveys consisting of over 1,000 volunteer hours. SDRPF uses Californian protocols for debris attribution during field surveys as described in the Rapid Trash Assessment tool (SWRCB, 2009). Their surveys cover 4.8 km^2 of riparian habitat abutted by urban development (Figure 1), and exclude two golf courses and a regional park considered free of debris loading. Volunteers survey and collect debris on a monthly basis (weekly visits that rotate locations) using Mappler, a mobile GIS platform, to geocode debris, and attribute a volumetric or mass estimate. Only aggregations of debris that were estimated to fill at least one 35-gallon trash bag were mapped. If the dominant material type has low density, such as plastic, then the number of 35-gallon (0.13 m^3) bags that could be filled by the debris was estimated and recorded. For large and dense debris objects, for example, a shopping cart, the number of trash bag equivalents was based on 16 kg per bag as measured by the SDRPF, but most of these items were excluded in our analysis (see next paragraph). Each geocoded debris site was assigned a source attribute, including inactive encampment, active encampment, dumping, litter, special removal needed, and stormwater debris. Stormwater debris was defined as debris that had previously been in the water column, and is found below high-water marks, with faded colors, silt marks, trash wrapped around roots, or other signs of decay. High densities may be found close to storm drain outfall locations, and smaller, light-weight, single-use items are more common (Chen, 2018). Dumped trash is characterized by larger items without evidence of decomposition, items in garbage bags or piles, can be close to vehicle access points. These protocols are similar to the differentiation of *litter patches* (accumulated trash) or *small* or *large illegal dumping sites* by Rech et al. (2015), who found that these categories could be successfully recorded by citizen scientists when compared to professional surveys. Site photos were included except for "active encampment" attributed sites to avoid personal identification (SDRPF, 2024).

Monthly data for water years 2019–2023 were downloaded and geospatial duplicates were removed, retaining only the most recent entry, then aggregated to the annual timestep. D was calculated as the difference in the total inventory of debris in October of a given year minus the total inventory in a previous year, plus the amount of removed debris (C, see Section 3.2.3). Only debris sites with categorical attributes "Litter", "Encampment Trash", "Dumping", and "Inactive Encampment" were chosen to represent direct debris dumping. "Special Removal Needed" debris sites were not considered since this debris is often heavier commercial and industrial debris composed of concrete, wood, and metals, such as old culverts, wooden pallets, and metal pipes, which are unlikely to be transported downstream. "Stormwater Debris" were not included in our accounting since it was assumed this debris originates from storm drains, and therefore is already accounted for in our estimate of indirect stormwater debris loading. "Stormwater Debris" sites recorded by SDRPF were proximal to storm drain outfall locations along the Lower San Diego River (Supplementary Figure 1 in Supporting Information S1). All data preparation was conducted in R (RStudio Team, 2022). The resulting annual water year data sets represent an estimate of annual riverine debris loading that is directly dumped into the river margin.

3.2.3. Cleaned-Up Debris (C)

Cleaned-up debris (C) was identified from the SDRPF data set as sites that were previously recorded as previously direct debris dumping ("litter", "dumping", or "encampment" attributes) or indirect stormwater debris ("stormwater debris" attribute), and were later marked with the attribute "Site no longer present" after clean-up. Geocoded locations (latitude and longitude) were checked to ensure correct matching of sites.

3.2.4. Inundated Trash Fraction ($F_{R,Y}$)

Our model of downstream debris transport (Equation 2) uses the floodplain inundation associated with the annual maximum flood to estimate the fraction of total debris in reach R available for transport in that year. This approach is based on recent research showing low correlations between debris transport and subseasonal changes in river flow, and a much more pronounced response to extreme discharge events (van Emmerik et al., 2023).

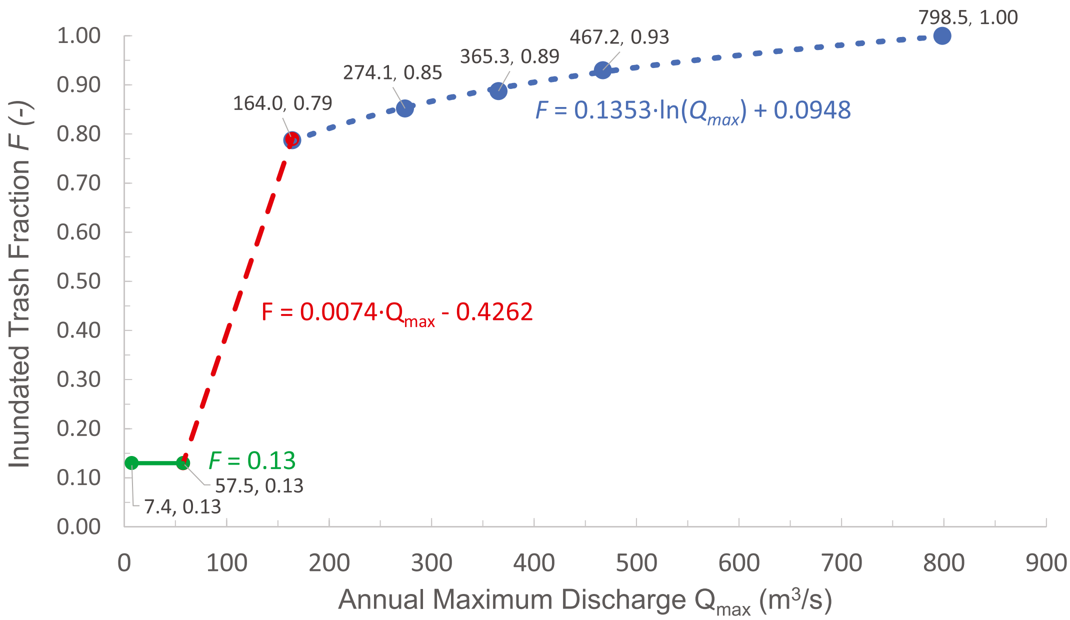

Figure 3. Inundated trash fraction F as a function of annual maximum discharge $Q_{\max}$. Solid green line represents discharge below bankfull inundation, red dashed linear relationship represents minor to moderate flood, blue dotted logarithmic relationship represents major flood.

The procedure used to estimate inundated debris for an arbitrary annual flood value is as follows. We collect inundation extent maps available for the river, and their related discharge values. In our case, 10-, 25-, 100-, and 500-year recurrence interval flood inundation maps and associated discharges were available from an existing report (Michael Baker International, 2018). Discharges relate to the USGS Gauge 11023000 (San Diego River at Fashion Valley) near the outlet of the San Diego River (Figure 1). For each inundation map, the inundation extent was intersected with observed locations of trash accumulations in each year (5 years of geocoded direct debris dumping data, SDRPF, 2024, Section 3.2.2). We calculated the average mass of trash inundated for each recurrence interval, as a fraction of all trash occurring in the 500–years floodplain, and took the mean over five years. These data were plotted as trash fraction against discharge, and could be accurately fitted using a logarithmic function (Figure 3).

At flows below the 10-year flood where no inundation mapping is available, we still require a relationship between trash fraction and discharge. Therefore, we make the following approximations. We set a "zero trash" discharge threshold below which no trash is expected to be inundated: we set this as the discharge below which debris concentration was zero as measured during stream sample surveys (7.4 m^3s^{-1}, Section 3.4). We set a "bankfull" threshold below which debris concentration is expected to be small because flows do not extend onto the floodplain. Bankfull discharge is set as the 2-year recurrence interval flow (57.5 m^3s^{-1}, calculated using a Gumbel distribution fitted to USGS discharge data). Inundated trash fraction between the zero trash and bankful discharges is estimated as the mean ratio of stormwater debris to total debris in our local data set (0.13, Section 3.2.2). This assumption is based on direct observations that stormwater debris is observed within and along the riverbank. For lack of other local information, we use linear interpolation between the inundated trash fractions at bankfull and 10-year flood.

The resulting piecewise equation that defines inundated trash fraction F as a function of annual flood discharge $Q_{\max}$ is given by Equation 3, and shown in Figure 3.

$$F = \begin{cases} 0 & Q_{max} < 7.4\ \text{m}^3/\text{s} & \textit{Zero Inundation} \\ 0.13 & 7.4\ \text{m}^3/\text{s} \le Q_{max} < 57.5\ \text{m}^3/\text{s} & \textit{Bankfull Inundation} \\ 0.0074(Q_{max}) - 0.4262 & 57.5\ \text{m}^3/\text{s} \le Q_{max} < 164.0\ \text{m}^3/\text{s} & \textit{Minor - Moderate Flood} \\ 0.1353\ ln(Q_{max}) + 0.0948 & 164.0\ \text{m}^3/\text{s} \le Q_{max} & \textit{Major Flood} \end{cases} \quad (3)$$

Equation 3 conforms to our expectations about how inundated trash fraction rises with discharge. Above bankfull discharge but below the 10-year flood, a rapidly increasing inundated fraction occurs as discharges inundate the floodplain. These moderate flood events may be where much of the work of riverine debris transport takes place, by analogy with sediment transport where the flood events that are both frequent and significant enough transport the most sediment rather than rare extreme floods (Wolman & Miller, 1960; Zakwan et al., 2022). Above the 10-year flood inundation mode, the logarithmic function represents only small increases in inundation extent with increasing discharges as documented for the Lower San Diego River (Michael Baker International, 2018).

Other rivers with different hydrogeomorphology may require adjustments in these proposed piecewise functions to fit local inundation information. Increasing discharge typically translates to increased debris transport, but the precise relationship is variable and largely undocumented (Cowger et al., 2022; van Emmerik, Tramoy, et al., 2019). We used the 2-year recurrence interval discharge to represent bankfull discharge, as used by the National Weather Service (National Weather Service, 2024), but an empirical bankfull stage could be established or adjusted as necessary for other watersheds. We were able to take advantage of geocoded datapoints for trash mass and location, but in watersheds without this information a simpler model could assume evenly dispersed debris in the floodplain.

3.2.5. Remobilization Probability, M

Remobilization probability M represents the probability that a piece of debris that is inundated by floodwaters in a given year will be entrained into the river flow. We estimated these probabilities empirically based on surveys of floodplain debris before and after inundation events. Remobilization may depend on many factors including size and material of debris, depth and velocity of water, number of inundation events and impacts of vegetation or sediment covering the debris. However, given our limited data to evaluate causes of remobilization, we tested two simplified models. (a) A single remobilization probability M applied to all debris pieces (b) A binned model with three functional size groups that allows for differences in M by debris size class: mega debris larger than 50 cm, macro debris between 5 and 50 cm, and meso debris between 0.5 and 5 cm, as measured by the longest size dimension (major axis). The model does not consider micro debris (<0.5 cm), which is outside the scope of this study and is typically several orders of magnitude lower in ocean emission mass than larger size classes (Meijer et al., 2021).

Empirical remobilization probabilities M for each size class were estimated as follows. The fraction of debris washed downstream was quantified during four rain events of sufficient magnitude (forecasted rain >13 mm) from November 2022 to March 2023. Two 5 × 5 m plots were established in each of two tributaries of the Lower San Diego River using measuring tape and wooden stakes driven into the streambed in each corner. Plots were geo-pinned with mobile devices in case stakes were washed away. High-visibility nylon rope was crosshatched to make 25 1 × 1 m quadrants. Digital photographs were taken pre- and post-storm event of each quadrant to compare the presence or absence of debris. Minimum and maximum cross-sectional lengths and visual material types were determined for each debris item. Functional size categories were applied—mega, macro, and meso—to each debris item consistent with The Ocean Cleanup (2023) size definitions. Individual debris items were considered remobilized if they were present during the pre-storm surveys but not the post-event surveys. Debris that was present in the survey plots pre- and post-storm did not remobilize (Supplementary Figure 2 and Supplementary Table 2 in Supporting Information S1). The resulting remobilization probabilities were:

$$R = \begin{cases} 0.54 \;\; for\ Mega\ Debris\ (>50\ \text{cm}) \\ 0.67 \;\; for\ Macro\ Debris\ (5\ \text{cm} - 50\ \text{cm}) \\ 0.71 \;\; for\ Meso\ Debris\ (0.5\ \text{cm} - 5\ \text{cm}) \end{cases} \tag{4}$$

The smallest debris, meso debris, remobilized at the highest rate (71%), followed by macro debris (67%), and then the largest, Mega debris (54%). An average remobilization probability $M = 0.64$ was used for the single rate model. Future models could apply and test additional size or material type or inundation event classifications and remobilization probabilities.

3.2.6. Downstream Transport Probability, N

The probability of debris items being transported downstream once inundated and remobilized (N) is taken from Meijer et al. (2021), where 59 panel experts were anonymously asked "what is the probability a piece of plastic will make it 1 km downstream in a year?", responding with a mean probability of 83%. We converted this result to a simple power expression (Equation 5), where the probability of downstream transport decreases with each kilometer downstream.

$$N = 0.83^{d} \tag{5}$$

where d is the distance in km from the center of the reach to the center of the adjacent downstream reach. Equation 5 has inherent simplifying assumptions, for example, that the mean probability (0.83) is applicable to all material types. In lieu of empirical evidence of transport distances through rivers, this probability function satisfies a broad approximation of downstream transport probability as a function of river length. There is some counterintuitive evidence that denser materials such as glass and metal may move more readily than plastic debris (McCormick & Hoellein, 2016), though insufficient data is available to estimate different values of N by material type.

3.3. Model Initialization

The model must be initialized to provide realistic debris concentrations at the beginning of the study period. A spin-up test showed that the model takes more than 100 years to reach steady state conditions when using 2019 static parameters (Supplementary Figure 3a in Supporting Information S1). Since widespread consumer plastics were introduced less than 100 years ago a more reasonable initialization period of 25 years was chosen representing a modern San Diego during which time population growth was lower than previous decades (U.S. Census Bureau, 2024). This simulation produced a mean floodplain debris density of 57 g m^{-2}, comparable to other riverine debris floodplain density estimates (McCormick & Hoellein, 2016). The model was therefore initialized for 25 years with a variable annual inundation proportion based on actual observed maximum discharges over that period (USGS, 2023) (Supplementary Figure 3b in Supporting Information S1).

3.4. Validation

We compared modeled ocean emissions (i.e., downstream debris transport at the river outlet) with net samples of debris taken near the watershed outlet during storm events. Our field estimates of mean annual load were based on annual flow volume and mean debris concentration from 18 net samples over 6 sampling events. We selected a sampling site where a road crosses the river channel 200 m downstream of the USGS flow gauge, with six culverts passing under the road (Figure 1). Our hand-deployed modified manta trawl net used a 0.093 m^2 aperture and 333 μm netting to collect debris samples during storm events (Supplementary Figure 4 in Supporting Information S1). We deployed the trawl net for 15 min, positioning it with the top of the net was just above the water surface to capture suspended and buoyant debris. In a few instances the net was pulled in before 15 min since either target riverine debris or non-target organic debris (mobilized vegetation, dirt, etc.) filled the net. Water velocity was measured prior to each net deployment using a Hach FH950 flow meter deployed in front of the culvert. Debris was air dried in the lab for 72 hr and weighed using a digital scale, then categorized by size and material type following Moore et al. (2011). Debris concentrations were calculated for each of the 6 events by dividing total event debris mass by total water volume flowing through the net during the deployment ($0.093\ m^2 \times \text{velocity ms}^{-1} \times (15 \times 60)\ s$) (Supplementary Table 3 in Supporting Information S1). Total annual flow volume at the nearby USGS gauge was multiplied by mean event concentration (0.35665 $g^1 m^{-3}$) to estimate annual total downstream transport load and compared to modeled ocean emissions.

Mean riverine debris concentration was used instead of a concentration-discharge relationship given current data limitations. Use of mean concentrations to estimate loads is recommended where data are scarce and uncertainties are high (Cowger et al., 2022; Roebroek et al., 2022; Stein & Ackerman, 2007). Our model accounts for non-buoyant debris materials including glass, metal, dense plastics, fabrics, and other non-buoyant consumer debris, these may be under-sampled in our surface trawl as dense items may be less likely to be transported downstream near surface (Cowger et al., 2021; Hoellein et al., 2014). However, given that our samples were taken at culvert outlets where mixing of the water column has occurred, we assumed that these samples were

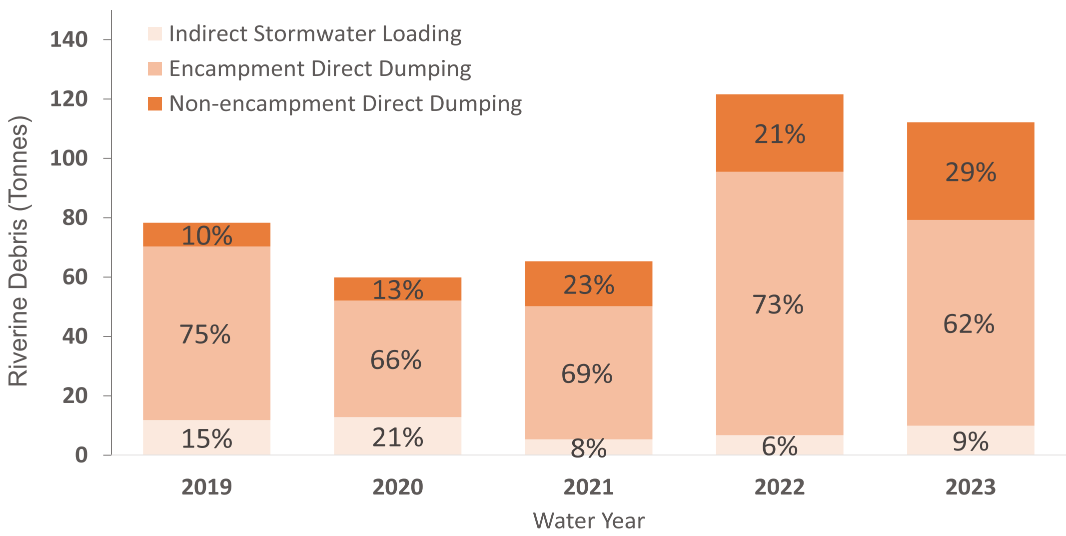

Figure 4. Lower San Diego River debris loading by source and water year with relative magnitudes (%).

representative of debris concentrations throughout the water column. We assumed that concentrations at the sample location (Lat/Lon 32.761,500, −117.205,833), are representative of those at the ocean outlet approximately 3.5 km downstream. Despite the simplifying assumptions, our validation followed the methods recommended by previous studies (e.g., Cowger et al., 2022) and provided independent estimates of emissions.

4. Results

We ran the model for five water years for the period 2019–2023 inclusive. The model requires annual maximum flow values that were taken from USGS Gauge 11023000 (San Diego River at Fashion Valley), and yearly records of debris locations and cleanup quantities that were provided by the San Diego River Park Foundation. Indirect stormwater loading values for the period were provided by Bagheri et al. (2024).

Examination of the model results enable us to analyze the magnitude of different sources of debris into the river channel (Section 4.1), evaluate the success of mitigations such as cleanup efforts (Section 4.2), assess trends in the quantity of debris stored in the river margins (Section 4.3), and quantify the mass of debris exported to the ocean and compare with loading, cleanup and storage mass (Section 4.4).

The following results present the model version using a single remobilization probability (see Section 3.2.5). A model with three debris sizes (meso, macro, mega) each having different debris remobilization probabilities was also tested but resulted in only small differences in ocean emissions and debris storage (2.1% higher and 1.3% lower respectively, see Supplementary Tables 4 and 5 in Supporting Information S1 for details). The simplicity of this model framework is conducive to future modifications, for example, incorporating size classes and/or material types into downstream transport probabilities, or further distinctions of debris sources within the two loading pathways.

4.1. Comparing Riverine Debris Loading Pathways

The model results show that total annual riverine debris loading (D + I), varies between 78 and 121 tonnes in the lower San Diego River (Figure 4). Direct dumping (D) accounts for most (79%–92%) of total loading, a majority of which is attributed to homeless encampments (62%–75% of total loading). Direct dumping is an order of magnitude larger than indirect stormwater inputs in 2021, 2022, and 2023, and over five times and three times larger in 2019 and 2020 respectively. Indirect stormwater inputs account for 8%–21% of total loading (Figure 4). To assess the sensitivity of the model to the buildup and washoff rates used to estimate indirect inputs, we ran a scenario using rates derived from Ballona Creek watershed in Los Angeles that has three times the population (Bagheri et al., 2024). In that scenario, indirect stormwater debris loads increased to 18%–43% of total annual loading, still well below direct dumping inputs (Supplementary Figure 5 in Supporting Information S1). In all water years, and in both the original and increased stormwater loading scenarios, direct debris loading attributed to homeless encampments is the greatest source.

2022 and 2023 show increases in encampment direct debris loading when compared to the early pandemic years of 2020 and 2021. We attribute this increase to greater levels of homelessness in the region. Internal SDRPF homelessness data shows a steady increase in the number of homeless encampments in the study area from a low of 26 in May of 2019 to a high of 135 in October 2022 (see Figure 2 in Hinds et al., 2024). City-wide data shows that homelessness more than doubled during a similar period from January 2019 to January 2023 (Regional Task Force on Homelessness, 2023). We tested for potential bias due to SDRPF survey effort, as measured by total volunteer hours, that could explain lower direct debris loading from 2020 to 2021 and increased loading in 2022 and 2023, but no significant difference was found (Supplementary Figure 6 in Supporting Information S1).

4.2. Impact of Cleanup Efforts on Mitigating Riverine Debris Storage and Ocean Emissions

One of two output pathways of riverine debris in the model is cleaned-up debris (C), representing ongoing mitigation efforts by the SDRPF to manually remove debris from the river corridor. Clean-up lowers debris accumulation rates and ocean emissions. From 2019 to 2023 the SDRPF cleaned up over 290 tons of riverine debris, with over 81 tons removed in 2023 alone. A model scenario excluding C increases stored riverine debris by 10%, 17%, 25%, 37%, and 48% from 2019 through 2023 (Figure 5a). Likewise, modeled annual ocean emissions are lower due to ongoing cleanup efforts than they otherwise would be if cleanup was excluded. Emissions are between 6 and 34 tonnes annually with ongoing cleanup efforts compared to between 7 and 60 tonnes in a hypothetical scenario without cleanup efforts. Without cleanup, ocean emissions increase by 9%, 20%, 32%, 49% and 74% from 2019 to 2023 (Figure 5b).

4.3. Accumulation of Riverine Debris Storage Over Time

Net accumulation of riverine debris was over 56 tonnes between 2019 and 2023. Net export (i.e., decreasing storage) of −0.5 and −4.0 tonnes occurred in water years 2020 and 2023 respectively, with increased ocean emissions in those years (Figure 6). Net increase in storage) of 9.9, 14.3 and 37.0 tonnes respectively occurred in years 2019, 2021, and 2022, when ocean emissions and cleaned-up debris were lower than the sum of direct and indirect loading. Riverine debris accumulation in the Lower San Diego River is also suggested by initialization results. During model initialization with 25 years of USGS maximum annual discharges, all but 3 years saw an increase in stored debris (Supplementary Figure 3b in Supporting Information S1).

We note that storage may be underestimated in the model, with corresponding overestimation of ocean emissions. This is due to the model assumption that all stored debris is subject to downstream transport and eventual export to the ocean, disregarding the chance that some stored debris is likely buried in river sediment, decreasing remobilization probabilities (Liro et al., 2020). Further development of the model to include long-term versus short-term storage compartments could help test this limiting assumption.

4.4. Ocean Emissions and Validation

Total ocean emissions, that is, riverine debris that becomes marine debris via downstream transport, is estimated as 82 tonnes during the period 2019–2023, with mean annual ocean emissions of 16.6 tonnes. During years with minor to moderate floods (2019, 2020, and 2023), ocean emissions increased with increasing discharge, amounting to 11.6, 24.7, and 34.4 tonnes, respectively. With lower flows (bankfull inundation) in 2021 and 2022, much lower ocean emissions - 5.8 and 6.1, respectively - were predicted. Most riverine debris is retained in the Lower San Diego River, consistent with findings from other studies (van Emmerik et al., 2022), with only a small fraction of the total stored debris (1%–6%) predicted to become marine debris in any given year (Figure 6 and Supplementary Table 6 in Supporting Information S1).

During validation, estimated annual emission from the net samples in 2023 was 19.6 tonnes, compared to 16.6 tons from the trash balance model. We used the mean sample concentration (0.36 g m^{-3}) to calculate the annual load, as recommended by Cowger et al. (2022) (Supplementary Table 3 in Supporting Information S1). Given the unknown uncertainty and lack of calibration of model parameters, the similarity between the two estimates lends credibility to model results. Total ocean emissions estimated from both stream sampling and model results are within one order of magnitude of the 5.5 tonnes estimated by a macroplastic-only model (The Ocean

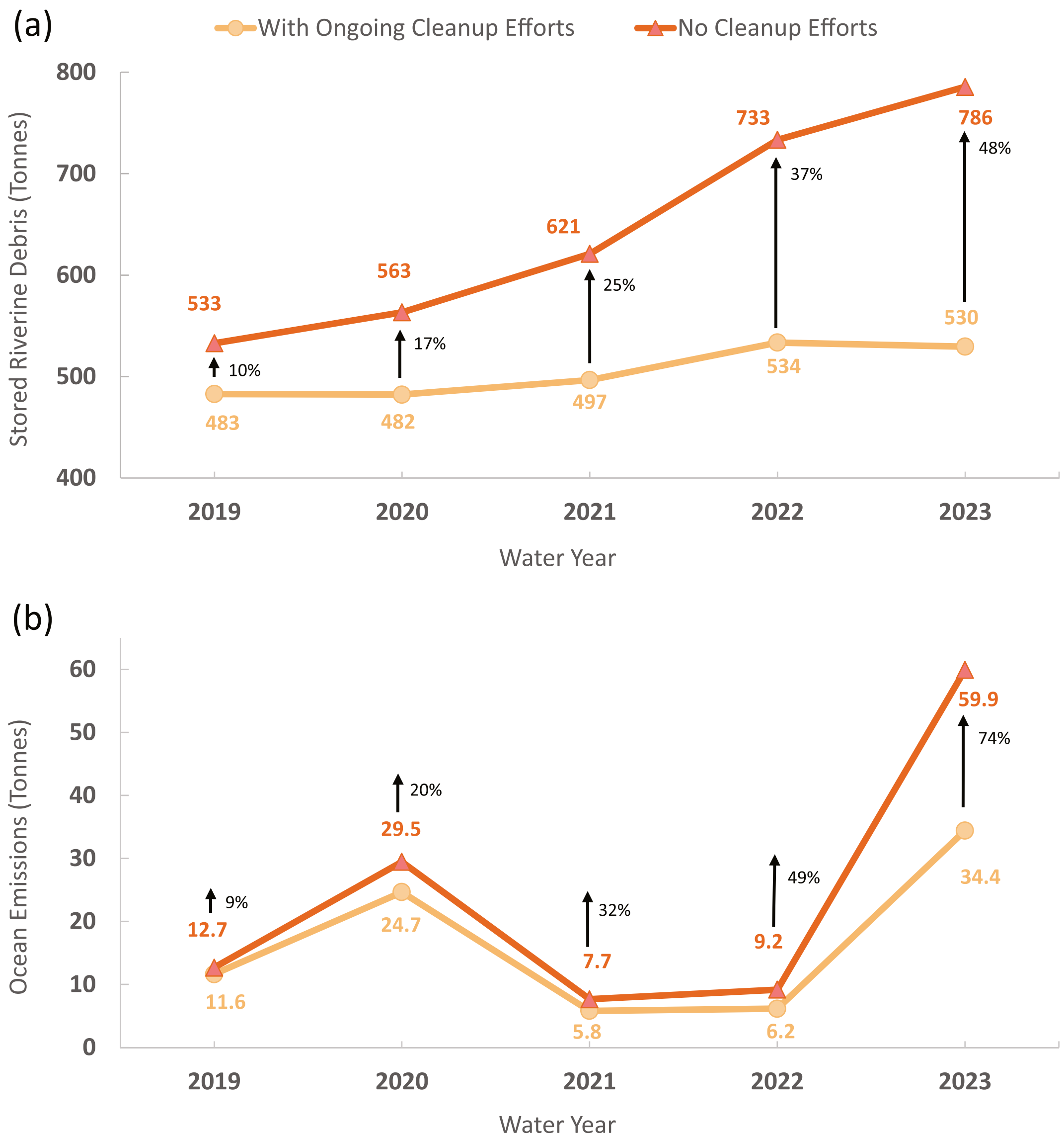

Figure 5. (a) Model-estimated total stored riverine debris in the Lower San Diego River floodplain with and without ongoing cleanup efforts. (b) Model-estimated ocean emissions with and without cleanup efforts. Arrows indicate increases from the status quo of ongoing cleanup efforts to the hypothetical scenario without those efforts.

Cleanup, 2023), and only several tonnes less than stream export of debris in Turkey Creek, an urban river in the Chicago metropolitan region with similar floodplain debris density (63.7 g m^{-2} compared to 57 g m^{-2} in Lower San Diego River) (McCormick & Hoellein, 2016).

5. Discussion

This study introduces a novel modeling approach to quantify riverine debris dynamics at the watershed scale. Integrating riverine debris loading data sets from community science surveys and from an open-source stormwater debris loading model gives a more complete picture of the sources, fate, and flux of harmful riverine debris. The model distinguishes two riverine debris loading pathways allowing for a comparison of loading magnitudes in an urban watershed. Data sets that further distinguish debris sources within loading pathways (i.e., homeless encampment debris within the direct debris dumping pathway) connect homelessness with its environmental impacts. This model framework provides a first estimate of the total accumulation of riverine debris in an urban river. With the incorporation of a debris cleanup data set as an output pathway we evaluate the efficacy of past

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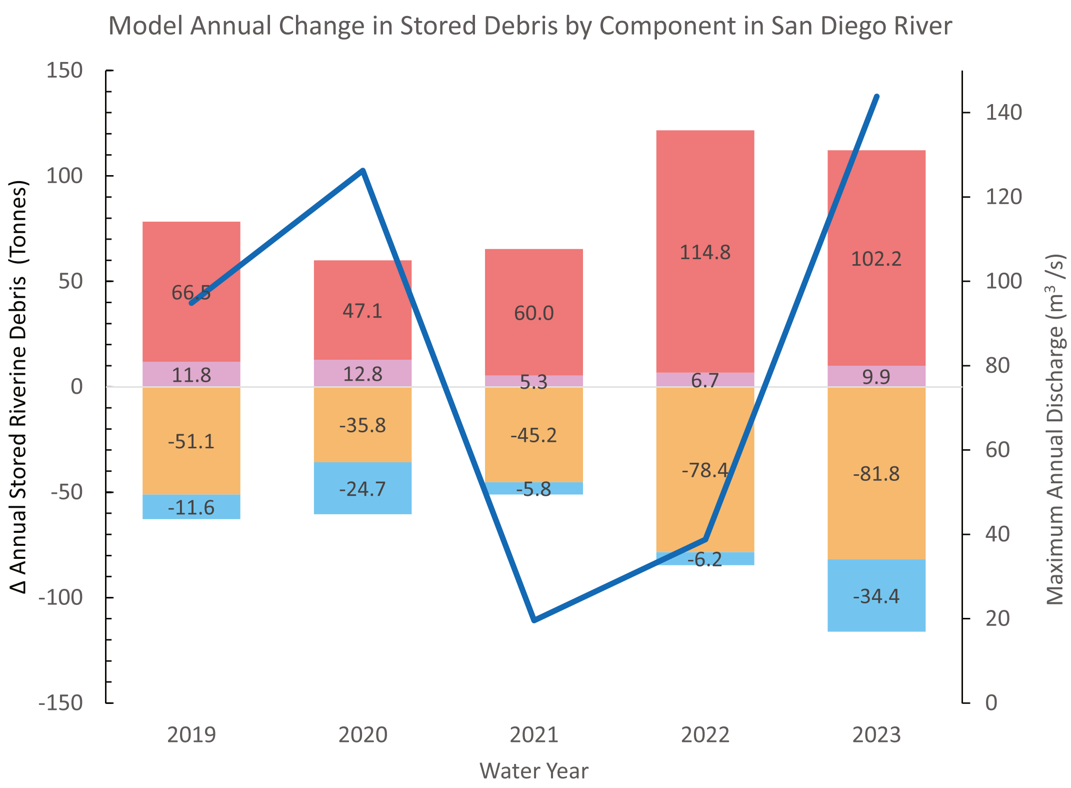

	2019	2020	2021	2022	2023
Net change	+9.9	-0.5	+14.3	+37.0	-4.0
OE/S	2%	5%	1%	1%	6%

Figure 6. Model change in stored (accumulated) debris by loading and output component. Blue line is maximum annual river discharge. Annual net change in storage and ratio (%) of ocean emissions (OE) to total stored debris (S) in lower box.

cleanup efforts within the riverine debris budget. Finally, the model estimates how much of the problem of riverine debris is transposed downstream to the problem of marine debris through ocean emissions.

5.1. Direct Dumping Is Dominant

Urban rivers are known major conduits of riverine debris, and ultimately marine debris (Meijer et al., 2021). More effective riverine debris mitigation measures at the watershed scale will benefit from a mass balance analysis such as the one conducted in this study. Differentiating between two loading pathways of riverine debris—indirect stormwater debris and direct debris dumping—highlights the relative magnitudes of debris origins, which vary from watershed to watershed and therefore necessitate different mitigation strategies. In the case of the Lower San Diego River, in all the studied water years, direct debris dumping is by far the dominant loading pathway. This result differs from other pollutants in the same river: recent studies show that the dominant source for fecal pollutant loading in the Lower San Diego River is not homeless encampments in the river corridor but rather sanitary sewer overflows and exfiltration from the public sewer system (Hinds et al., 2024; Schiff et al., 2024). Though direct dumping of plastics and other waste into the river corridor is well documented in many watersheds (Rech et al., 2015; van Emmerik & Schwarz, 2020; Williams & Simmons, 1999), this study highlights the critical nature of cleanup efforts within the urban floodplain (see Section 5.3). Alternative mitigation strategies, such as installing trash full capture systems in municipal storm drains to address indirect stormwater debris, as required under the California Trash Amendments (California Environmental Protection Agency, 2015), may not reduce total riverine debris loading if direct deposition is the dominant source. Given limited mitigation resources, prioritizing direct debris dumping mitigation over indirect stormwater debris mitigation, especially where the crisis of homelessness is prevalent in the urban floodplain, would have the greatest impact.

5.2. Homelessness Inextricably Linked to Riverine Debris

In all modeled years, the largest single source of riverine debris was direct debris dumping associated with homeless encampments. This result highlights that homelessness is not simply a humanitarian crisis but also an acute environmental crisis (Flanigan & Welsh, 2020). In the Lower San Diego River, trends in debris loading mirror trends in local unsheltered homelessness. Less encampment debris, and consequently lower riverine debris loading, was observed in water years 2020 and 2021, consistent with fewer unsheltered homeless persons and encampments. By water year 2023 the sharp increase in homelessness following the COVID-19 pandemic is reflected in a sharp increase in direct debris dumping (Figure 4). Possible explanations of the dramatic increases in encampment-sourced direct debris loading in 2022, and to a lesser extent in 2023, is the winding down of pandemic shelter assistance programs (Suliman, 2023) and a rapid post-pandemic increase in housing costs which is a known contributing factor of homelessness (O'Regan et al., 2021). Two disparate problems of homelessness and riverine and marine debris are closely connected, raising awareness that solutions for one could shape the outcomes for the other.

5.3. Floodplain Cleanup Efforts Are Critical to Riverine Debris Mitigation

The importance of floodplain cleanup efforts is evident in the dominance of direct debris dumping over indirect stormwater debris. Though this mitigation strategy does not necessarily discriminate a specific debris loading pathway—indirect stormwater debris is also cleaned up downstream of its source—floodplain cleanup efforts reduced the debris stored in the floodplain (Figure 5b), which limits downstream emissions. Removing riverine debris at the source may be a crucial strategy as mobilized debris often becomes entangled in vegetation (van Emmerik & Schwarz, 2020) or buried in sediment (van Emmerik et al., 2022), making downstream cleanup more difficult. When floodplain cleanup efforts were removed from the model, annual estimated ocean emissions increased, and at an accelerating rate each year (Figures 5a and 5b). For example, in 2023 eliminating cleanup in the model resulted in a 74% increase (25 tons) in ocean emissions. We conclude that community cleanup efforts play an important role in reducing riverine debris accumulation in the Lower San Diego River. Pairing scientific surveys of riverine debris with community cleanups has previously been recommended to document the success of this strategy (Rech et al., 2015).

5.4. Riverine Debris Accumulates in River Corridors

Despite ongoing mitigation efforts in reducing riverine debris in the Lower San Diego River, our results indicate that debris continues to accumulate in the river corridor. In the Lower San Diego River this accumulation trend is supported by model initialization runs which could not achieve steady state debris concentration in a 100-year model run. This is consistent with the historical record of emergence and increasing use of consumer plastics, which are already abundant in the Lower San Diego River (Supplementary Figure 7 in Supporting Information S1) and in other urban rivers (McCormick & Hoellein, 2016). Previous work has shown that consumer waste production increases with population (Hoornweg et al., 2013), and over the past three decades San Diego's population has increased over 31% (U.S. Census Bureau, 2024). The population growth includes a notable recent increase in persons experiencing homelessness. Growth of both overall and homeless populations contribute to riverine debris loading and support the accumulation trend seen in model results (Figure 5b).

Reducing the storage of debris in the river corridor and passing "peak trash" will require a change of the status quo. If the California Trash Amendments remove most indirect stormwater debris loading, and floodplain cleanup efforts increase, we would expect peak riverine debris in the Lower San Diego River to occur sooner, followed by a reduction in riverine debris. Achieving this reduction in the Lower San Diego River warrants a holistic approach to mitigation that addresses both loading pathways and includes reductions in homeless encampment debris. With many other urban rivers facing similar, or worse, accumulation trends (Nyberg et al., 2023), the application of this model to those watersheds would illuminate the local riverine debris budget.

5.5. Ocean Emissions Fluctuate With Flooding but Most Debris Stored in Floodplain

Even in years with elevated maximum discharges (i.e., 2020, 2023), most (94%–99%) riverine debris is retained in the river corridor on an annual basis. This finding agrees with previous literature that estimates in an urban watershed only about 3% of plastic debris that is introduced into the environment will ultimately reach the ocean (van Emmerik, Loozen, et al., 2019). Similar roles of floodplain storage have been documented for sediment, where it can take decades for contaminated sediment to move through the river-floodplain complex (Malmon et al., 2002).

The trash balance model assumes that the maximum annual discharge is an accurate predictor of downstream debris transport, since only larger floods inundate the floodplain and mobilize stored debris. This simplifying assumption aligns with evidence that higher discharges are the main transport mechanism of riverine debris in an urban river (van Emmerik et al., 2023). Evidence for this mechanism in the Lower San Diego River comes from in-situ stream sampling measurements, where riverine debris was only captured during the rising limb of the hydrograph, and at elevated gauge heights (Supplementary Table 3 in Supporting Information S1). Transport dependent on maximum discharge combined with large interannual variability in annual maximum flood size results in highly variable annual ocean emissions (Figure 6). However, annual load extrapolated from stream samples using the mean concentration method (Cowger et al., 2022) was comparable with model mean ocean emissions. This suggests model ocean emissions are a good first order approximation of actual annual ocean emissions.

We compared our modeled ocean debris emissions, at 16.6 tonnes/yr, to previous estimates for San Diego River emissions provided by global models. Our results are somewhat higher than the 5.5 tonnes/yr estimated by a recent global macroplastic-only model that accounts for population, waste production, precipitation, terrain and land-use effects (Meijer et al., 2021; The Ocean Cleanup, 2023). Our results are much higher than the 0.0094 tonnes/yr estimated by an earlier study based on population and waste production per country (Lebreton et al., 2017). These comparisons show it is critical to account for individual river basin characteristics. Our study demonstrates the importance of information on direct dumping behavior and homeless populations in the river corridor. These findings could be applied globally by including similar urban rivers into the empirical data used to constrain global models, and by including indicators of direct dumping and homelessness into global methods for spatial extrapolation. Incorporating such information into global models will be necessary to refine spatial distributions of ocean debris emissions to accurately simulate urban rivers.

5.6. Limitations

The model has simplifying assumptions that suggest avenues for future research. The model uses an annual water year timestep, commensurate with data sources such as debris loading rates and stored volumes that are often available on an annual basis. Where higher resolution data is available, the model could be run on a monthly or shorter timestep. This could improve representation of debris transport during intra-annual floods, compared to the current assumption that the annual maximum discharge is the primary control on transport. Such a model could also account for seasonal changes in indirect stormwater loading, clean-up flux and debris storage.

The model uses estimates of the probability that floodplain debris is remobilized into the channel. If additional data were available, these probabilities could be updated to account for varying water depth, velocity and resulting shear stress. Remobilization probabilities may decline as debris becomes entangled in vegetation or buried in sediment, and could be adjusted for vegetation density. Our model assumes that the fraction of floodplain debris that is inundated is linear between bankfull and 10-year flood stage. HEC-RAS or a similar model could be used to define a more accurate relationship by estimating inundation for intermediate flood sizes, accounting for reach-specific topography.

Model results could be refined by gathering more riverine debris concentration samples during storm events to constrain the relationship between discharge and downstream transport. All the net samples of debris used for validation were taken below bankfull flow for safety and accessibility, and may therefore underestimate transport at high flows. Future studies could include sampling at higher flows, although similar efforts found that sampling often had to stop due to dangerous conditions (Cowger et al., 2022) so other methods such as traps in the floodplain could be developed.

6. Conclusion

We developed a holistic watershed-scale model that simulates accumulation, transport and export of debris (plastic and other mismanaged consumer waste) through an urban river system. The model informs effective mitigation efforts by improving understanding on the origin, transport, and fate of riverine debris (Hoellein & Rochman, 2021; van Emmerik & Schwarz, 2020). We applied the model to simulate the Lower San Diego River, an urban river in southern California where debris stored in the river corridor and exported to the ocean are current environmental concerns.

Our results show that direct dumping into the river corridor outweighs inputs of debris through stormwater drains. The majority of direct dumping is attributed to homeless encampments (62%–75% of total loading). Despite the efforts of a community organization that removes significant quantities of this debris from the floodplain, riverine debris continues to accumulate in the Lower San Diego River. Future floods are therefore expected to emit increasing quantities of marine debris unless mitigation efforts improve and tip the balance from a continued accumulation phase toward a reduction in stored riverine debris. Model results are valuable to guide mitigation efforts: such efforts in the Lower San Diego River should target direct dumping in preference to reducing stormwater inputs. This modeling framework is applicable to other urban rivers where comparable estimates of stormwater loading, direct dumping and clean-up are available. The results may suggest differing mitigation recommendations depending on local conditions; for example, direct dumping may be less prevalent in river corridors with smaller homeless populations.

Our results provide a first estimate of the pathways, mechanisms, and quantities of riverine debris in an urban river, but many uncertainties remain in the mass balance of riverine debris. The role of the floodplain as a store and chronic source of remobilized debris is particularly important and uncertain. Incorporating sedimentation and its role in debris storage could further quantify how rivers are both long- and short-term reservoirs of debris (Liro et al., 2020). Including object sizes, material compositions and associated transport probabilities could refine downstream transport quantities. More validation data would further substantiate the model, refine the discharge concentration relationship (Cowger et al., 2022), and further explore the role of extreme flood events and maximum discharge as an effective predictor of debris transport (van Emmerik et al., 2023).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Community science survey data describing floodplain debris in the Lower San Diego River are maintained by the San Diego River Park Foundation. Current data are available at https://immappler.com/sandiegorivertrash/. Field data describing remobilization fractions are presented in Supplementary Table 2 in Supporting Information S1. Field data describing debris load in storm event river samples are presented in Supplementary Table 3 in Supporting Information S1. Results used to create Figure 6 describing change in stored debris by loading and output component are presented in Supplementary Table 6 in Supporting Information S1. All field and analysis data is available as a Zenodo release at https://doi.org/10.5281/zenodo.15002757 and via the NOAA Marine Debris Clearinghouse repository https://clearinghouse.marinedebris.noaa.gov/project?mode=View&projectId=2230.

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