



From rainfall to seafloor: Tracing riverine and urban stormwater litter transport in Mediterranean fishing grounds through systematic meteorological station testing

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ABSTRACT

Precipitation can mobilize terrestrial litter into coastal waters through urban stormwater pathways, potentially including combined sewer outflows (CSOs), but establishing quantitative relationships between rainfall and benthic litter accumulation has proven challenging. River discharge adds complexity by potentially washing litter away from fishing grounds. We tested 54 meteorological station-fishing ground combinations across nine ports in the northwestern Mediterranean (2019–2024, 236 trawl hauls), examining precipitation windows from 2 to 20 weeks and river discharge effects at six connected sites. Precipitation served as a proxy for urban stormwater input, including CSO activation, which was not directly measured.

Station selection critically determined detected effects: within Vilanova i la Geltrú alone, station choice produced estimates ranging from –62% to +88% per 10 mm precipitation, showing that proximity alone does not guarantee hydrological connectivity. Two port types emerged: Type A, a positive precipitation response ($n = 7$, 5 significant) consistent with urban stormwater delivery, and Type B, river washout ($n = 2$, negative effects). Rivers predominantly removed rather than delivered litter: five of six connected ports showed washout effects (–13.1% to –100% per 100 m³/s discharge). Only Vilanova i la Geltrú showed positive river effects (+12%), reflecting downstream accumulation from Barcelona via the Llobregat River plus a strong local precipitation response (+88%). Temporal signatures differed for most ports: positive precipitation effects typically peaked within 2–5 weeks (4 of 5 significant ports) versus 12–18 weeks for rivers, with L'Ametlla de Mar (16 weeks) as an exception; the specific mechanism was not directly confirmed.

Management strategies should be location-specific: urban stormwater infrastructure for Type A ports, upstream river management for Type B, and coordinated approaches for multi-source zones. Urban precipitation-associated inputs, plausibly linked to CSO activity, emerge as the primary correlate of benthic litter delivery.

1. Introduction

Marine litter, defined as persistent, manufactured or processed solid materials discarded into marine and coastal environments, has risen sharply with single-use products and waste management gaps. Plastics dominate the litter spectrum, often dominating beach, surface, and seafloor litter (Bergmann et al., 2015). Millions of tons of plastic enter the ocean annually from coastal populations (Spedicato et al., 2019; Canals et al., 2020). Because plastics persist and fragment rather than degrade, their impacts extend from habitat alteration and entanglement to trophic transfer and potential human exposure (Bergmann et al., 2015).

Marine litter arises from both land-based and sea-based activities (Bergmann et al., 2015; Canals et al., 2020; Jeftić et al., 2009; Blanco et al., 2025). Land-based inputs include riverine transport, stormwater runoff, combined sewer overflows (CSOs), coastal tourism, waste mismanagement, and industrial discharges. Sea-based sources encompass maritime transport, fishing and aquaculture, and offshore activities (Bergmann et al., 2015; Jeftić et al., 2009; Angiolillo and Fortibuoni, 2020; Blanco et al., 2025). Items differ in buoyancy, transport and settling behavior, shaping their eventual fate on the seabed (Galgani et al., 2010; Bergmann et al., 2015).

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The Mediterranean Sea is a sentinel for marine pollution: semi-enclosed basin with limited water exchange, dense coastal human populations, and intense maritime traffic (Galgani et al., 2010; Spedicato et al., 2019). Regional assessments report high plastic amounts in seafloor litter (e.g., 63% in the Northwestern Mediterranean), with concentrations linked to river mouths, outfalls, and urbanized shorelines (Blanco et al., 2025; Galgani et al., 2010). Storm events rapidly mobilize debris into coastal waters (Galgani et al., 2010; Canals et al., 2020). Policy solutions such as fisher-led litter recovery credit programs have been proposed (Galimany et al., 2019), but effectiveness depends on understanding transport mechanisms, which remain poorly characterized.

Land-based inputs reach the sea via two principal routes. Rivers integrate diffuse catchment sources, delivering litter continuously with storm-flood pulses increasing transport capacity (Galgani et al., 2010; Bergmann et al., 2015; Canals et al., 2020; Blanco et al., 2025). Urban drainage systems act as point sources: stormwater and CSOs inject large debris quantities during rainfall (Galgani et al., 2010; Blanco et al., 2025). At sea, currents redistribute floating debris (Galgani et al., 2010; Spedicato et al., 2019), while submarine canyons funnel materials downslope, creating accumulation hotspots through storm-induced currents and shelf water cascading (Tubau et al., 2015). Flash floods in the Messina Strait created sediment gravity flows funneling massive land-based litter to the deep sea, resulting in the highest deep-sea litter density ever observed (Pierdomenico et al., 2019). Understanding the relative importance of these pathways is essential for management.

Despite progress on floating and shoreline debris, drivers linking precipitation to seafloor litter remain poorly quantified. Studies report correlations between river discharge and floating litter with weekly lags, but quantitative evidence for precipitation-to-benthic accumulation is lacking, particularly where rainfall triggers CSOs (Galgani et al., 2010; Spedicato et al., 2019; Blanco et al., 2025; Araya-Campano et al., 2026; Biancardi et al., 2026). Precipitation is often used as a broad proxy for both riverine and urban inputs, making it difficult to disentangle mechanisms or identify relevant temporal windows. Addressing this gap is central to regional policy frameworks such as the Marine Strategy Framework Directive (MSFD) and the Barcelona Convention, which identify seafloor litter as a key descriptor for Good Environmental Status (GES).

The Catalan margin (NW Mediterranean) offers an ideal natural laboratory. The region combines multiple river systems (e.g., Ebro, Ter, Llobregat), strong urbanization gradients, several fishing ports, and dense hydrological monitoring networks. Its Mediterranean climate, dominated by episodic storms and prolonged dry periods, creates distinct temporal patterns enabling evaluation of both short-lived urban pulses and delayed catchment responses. This diversity allows testing both single-source ports (CSO-only or river-only) and potential multi-source accumulation zones where multiple pathways converge.

We investigate whether urban precipitation (proxy for CSO activation) and river discharge exert different effects on benthic litter, how these vary geographically along the Catalan coast (2019–2024), and which temporal windows capture each mechanism. We test four hypotheses: (H1) river discharge exerts broadly positive influence on seafloor litter by integrating watershed inputs and continuously delivering materials seaward; (H2) urban drainage has spatially restricted impacts, as CSOs are point sources predominantly affecting nearby grounds; (H3) the pathways exhibit distinct temporal signatures, with urban runoff responding rapidly while river-mediated inputs involve longer lags; and (H4) spatial patterns reflect source geometry, with rivers influencing broader coastal stretches while CSOs produce localized footprints.

Our bottom-trawler sampling method, based on Fishing for Litter strategies (Ronchi et al., 2019), may underestimate debris loads and miss some marine litter (e.g., monofilaments) due to gear selectivity (Watters et al., 2010). We account for these limitations when interpreting results and discuss implications for monitoring and management under MSFD and related policies.

2. Methods

2.1. Study area and sampling design

Bottom-trawl surveys were conducted along the Catalan coast (NW Mediterranean) from 2019 to 2024 as part of the ICATMAR fisheries monitoring program (Carreton et al., 2025), at depths of 50–800 m, or a minimum of 3 nautical miles from shore in shallower areas (Council of the European Union, 1994, 2006). Marine litter was collected by commercial trawling vessels operating from nine major fishing ports (Fig. 1, Supplementary Figure S1). In this study, “ports” refer to the home bases of the trawler vessels, not the locations where litter was sampled; all litter data were collected from fishing grounds (offshore sampling locations) that may be situated several kilometers from the port itself (Fig. 1). The geographic coordinates recorded for each haul represent the center of the trawled area.

Several ports (La Ràpita, Roses) sit in sheltered bays yet trawl adjacent open waters, so CSO discharge must be transported offshore before detection; some ports may also function as multi-source accumulation zones receiving both local CSO and upstream river inputs.

The full ICATMAR dataset for these nine ports consists of 612 hauls collected between 2019 and 2024 (Ribera-Altimir et al., 2023). For this analysis, we selected 236 hauls with complete hydrological data (precipitation and river discharge records within temporal windows) and quality-controlled litter mass. For each haul, the following variables were recorded: total litter mass (kg), mass by litter category, trawling time (hours) and precise geospatial coordinates. These measurements enabled standardization of litter mass by fishing effort (kg/hour); each haul corresponds to a standardized trawl deployment geolocated at the center of the trawled path. Litter items were identified and classified following the Regulation (EU) 2022/92 (Balcells et al., 2023). In this work, we reclassified the ICATMAR categories into a functional framework defined by density and source: light-urban (plastics and textiles), heavy-urban (glass, metal, and rubber), and heavy-industrial (processed wood, clinker, and construction materials). These categories reflect differences in buoyancy, transport behavior, and likely source pathways (consumer-derived versus urban/industrial), enabling exploration of type-specific responses to precipitation and river discharge.

2.2. Hydrological data

Precipitation data for 2019–2024 were obtained from the *Xarxa d'Estacions Meteorològiques Automàtiques* (XEMA), a network of 170 automated meteorological stations operated by the Catalan Meteorological Service (*Servei Meteorològic de Catalunya*, 2025). XEMA stations record precipitation at 30-minute intervals, which we aggregated to daily totals (mm/day) for analysis.

To validate hydrological specificity and ensure detected river effects reflect genuine connectivity rather than spurious correlations, we tested two rivers where no influence was expected due to geographic barriers: the Ebro (*Confederación Hidrográfica del Ebro*, 2026), whose delta geomorphology shields the fishing grounds at La Ràpita and L'Ametlla de Mar despite its large catchment (85,530 km²), and the Rhône (*Ministère de la Transition Écologique* et al., 2024), separated from our northernmost site (Roses) by over 100 km and a wide Gulf of Lions.

For hydrologically connected ports, each fishing ground was paired with the nearest river carrying an ACA discharge gauge. Arenys de Mar, in the Maresme county, has no dedicated river nearby; the Tordera was therefore tested against both the Arenys de Mar and Blanes fishing grounds.

In the Mediterranean context, wastewater treatment plants commonly operate near full capacity; during heavy rainfall, combined sewer overflow (CSO) events release untreated or partially treated effluent into coastal waters. We used precipitation (mm/day) as a proxy for CSO activation, assuming precipitation intensity correlates with discharge volume, and identified 33 active coastal discharge points

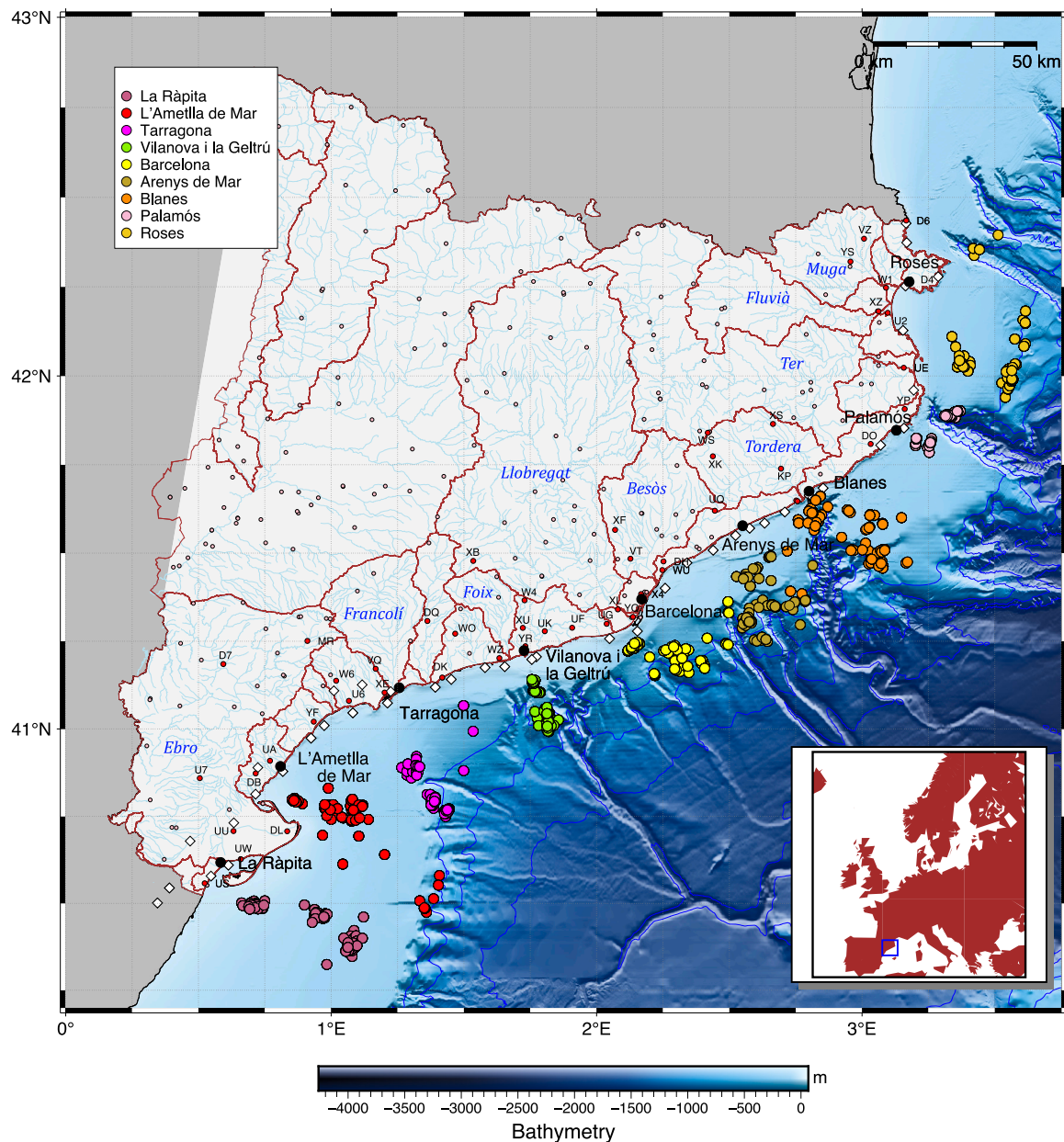


Fig. 1. Map of Catalonia showing the 9 ports, haul locations (color-coded by home port), rivers (blue lines), river drainage basin boundaries (brown outlines; labeled basins indicate rivers used in analysis), XEMA precipitation stations (inland pink dots; inland red circles with labels show stations used in analysis), and submarine emissaries (white diamonds). Inset shows regional context. Bathymetry data from EMODnet (EMODnet Bathymetry Consortium, 2024). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(WWTP outfalls and CSOs) within 20 km of the fishing ports (EU UWWTD, 2025).

Distances between ports and candidate XEMA stations were evaluated for all potential combinations. Stations located more than 10 km from the port centroid were generally excluded, as coastal precipitation in the Mediterranean often exhibits steep spatial gradients at 5–10 km scales (Lobligeois et al., 2014; Marra et al., 2022). Arenys de Mar, lacking suitable stations within 10 km, was included at a second stage using stations within 20 km.

2.3. Statistical analysis

2.3.1. Lagged cross-correlation and feature engineering

A key challenge in linking precipitation to benthic marine litter is identifying which meteorological stations best represent hydrological

connectivity between urban stormwater systems, particularly CSOs, and nearby trawling grounds. Rather than relying solely on the nearest station, we conducted a systematic sensitivity analysis testing multiple candidate stations per port.

To capture the cumulative impact of rainfall, we generated rolling precipitation averages for 2-, 3-, 4-, 5-, 6-, 8-, 10-, 12-, 16-, and 20-week lag windows, and quantified the relationship between lagged precipitation and litter abundance using Spearman's rank correlation, selected for its robustness to outliers in non-normal mass data. Lags from 0 to 52 weeks were evaluated to identify the “optimal lag”, the temporal offset yielding the strongest land–sea correlation per port.

Across all ports, we evaluated 3–10 candidate XEMA stations within 50 km of each site (Supplementary S1). Station prioritization followed three criteria: stations situated within the coastal watershed upstream of the trawling areas, consistent with the predominant north-to-south current along the Catalan margin (Martínez et al., 2024); stations at

positions likely to capture urban stormwater signals more broadly (of which CSO activation is one plausible component); and >80% data completeness throughout the study window. This process yielded 54 port-station combinations across nine ports.

2.3.2. Model fitting and window selection

To quantify these relationships while accounting for overdispersion, we employed a Negative Binomial Generalized Linear Model (GLM), appropriate here because variance in litter mass across hauls typically exceeds the mean.

The GLM formulation used to estimate litter mass is:

$$\ln(\mu) = \beta_0 + \beta_1 \cdot P_{lag} + \beta_2 \cdot \sin\left(\frac{2\pi \cdot \text{week}}{52}\right) + \beta_3 \cdot \cos\left(\frac{2\pi \cdot \text{week}}{52}\right) + \sum \beta_{port_i} \cdot Port_i + \log(E), \quad (1)$$

where μ is expected standardized litter mass (kg/hour), β_1 is the precipitation coefficient, P_{lag} is precipitation accumulated over the optimal lag window, β_2 and β_3 capture annual seasonality, β_{port_i} are port fixed effects, and $\ln(E)$ is the offset for trawling effort. The log link makes effects multiplicative (e.g., $\beta_1=0.05$ multiplies expected litter mass by $\exp(0.05) \approx 1.05$, a 5% increase per unit; see Supplementary Material Table 1).

β_1 quantifies the effect of cumulative precipitation on litter mass, reported as percentage change per 10 mm precipitation:

$$\text{Effect} = [\exp(\beta_1 \times 10) - 1] \times 100\%. \quad (2)$$

For river discharge, effects represent percentage change per 100 m³/s:

$$\text{Effect} = [\exp(\beta_1 \times 100) - 1] \times 100\%. \quad (3)$$

Selection of optimal precipitation windows (2–20 weeks) was based on AIC. To prevent overfitting, we applied a parsimony rule: when two windows had $\Delta\text{AIC} < 2$, the shorter window was selected (Burnham and Anderson, 2004), prioritizing interpretability given the relatively sparse haul data (~16 hauls per port over five years).

Station selection followed the a priori hydrological and infrastructural criteria described above (watershed position, proximity to documented urban stormwater discharge points, and data completeness), established independently of model results. Where multiple candidate stations satisfied these criteria comparably for a given port, we denote the station most consistent with these criteria as the optimal station in the main text, and report the full distribution of results across all tested stations for every port in Supplementary Table 4. This full multi-station distribution serves as a sensitivity analysis, allowing readers to evaluate whether conclusions depend on the specific optimal station chosen or hold more broadly across the tested station set.

95% confidence intervals for all reported precipitation and river discharge effects were computed directly from each model's estimated standard error, on the linear predictor (log) scale, and back-transformed to the percentage-effect scale reported throughout; full intervals for all 50 tested station-port combinations (Fig. 2) and all 9 tested river discharge models (Fig. 3) are reported in Supplementary Tables 4 and 5, respectively.

2.3.3. Multiple comparisons correction

Because the 9 primary port-level results (Table 1) and the 9 river discharge results (Supplementary Table 5) each constitute a family of hypothesis tests, we applied the Benjamini–Hochberg false discovery rate (FDR) procedure (Benjamini and Hochberg, 1995) to each family separately, at $\alpha = 0.05$. This procedure was chosen over the more conservative Bonferroni correction as more appropriate for hypothesis-generating environmental data with potentially correlated tests across neighboring stations and river systems. Adjusted significance (BH-FDR) is reported alongside nominal p-values in Table 1 and Supplementary Table 5. The broader 50-combination station-sensitivity panel (Supplementary Table 4) and the 27 litter type-specific tests (Section 3.4)

are explicitly treated as exploratory and sensitivity analyses rather than confirmatory hypothesis tests, and are not subject to family-wise correction; we report raw p-values for these panels and interpret them with corresponding caution (Section 4.7).

3. Results

3.1. Optimal precipitation window determination

Optimal windows ranged from 2 weeks to 18 weeks across ports (Supplementary Figure S2). Positive precipitation responses spanned 2–16 weeks (median 5 weeks, $n=5$ ports), with 4 of 5 clustering at 2–5 weeks; L'Ametlla de Mar, the weakest of the 5 (+3.4%), was a 16-week exception falling within the slower river-timescale range. River-mediated washout processes spanned 12–18 weeks ($n=4$ ports). With this exception noted, a broad separation between rapid urban-runoff and slower river-mediated timescales remains apparent, though it is not a strict bimodal split.

3.2. Overall testing results

We evaluated 54 unique port-meteorological station combinations, obtaining successful model fits for 50 of them (92.6%) (Table 1 and Supplementary Material Table 4). Precipitation effects on total benthic marine litter showed substantial spatial heterogeneity, both among ports and among stations within the same port, ranging from strongly positive to strongly negative depending on local hydrological context.

All nine primary port-level effects remain classified consistently before and after Benjamini–Hochberg correction: the seven nominally significant effects (La Ràpita, L'Ametlla de Mar, Tarragona, Vilanova i la Geltrú, Barcelona, Blanes, Roses) all retain $q(\text{BH}) < 0.05$, and the two nominally non-significant effects (Arenys de Mar, Palamós) remain non-significant. Barcelona showed the smallest margin ($q=0.043$), warranting some additional caution relative to the other significant ports. Further diagnostic plots and tables can be found in the Supplementary Material.

Across all fishing grounds, estimated precipitation effects spanned a wide range (Table 1), illustrating the critical influence of station selection (Fig. 2A). Within single ports, different stations captured distinct hydrological signatures (positive precipitation response, washout, or mixed influences), producing divergent effect directions. Vilanova i la Geltrú displayed the greatest internal variability, with effects ranging from –62% to +88% (>150-percentage-point range, Fig. 2B), exceeding all between-port variability.

Confidence intervals varied substantially across stations (Fig. 2); several non-optimal stations with wide, zero-crossing intervals (e.g., Tarragona station XB, Roses station D4) illustrate the reduced precision obtained when station selection does not follow the hydrological criteria in Section 2.3, reinforcing the case for principled over nearest-neighbor selection.

3.2.1. Port classification by behavioral consistency

Type A: Positive-Direction Ports ($n = 7$)

Seven ports showed a positive point estimate for the precipitation effect (Table 1), though this direction was statistically supported in only five: Roses (U2: +99.3%, $p = 0.021$, 2-week window), Vilanova i la Geltrú (XU: +88.4%, $p = 0.0003$, 2-week window), La Ràpita (UW: +60.5%, $p < 0.001$, 5-week window), Barcelona (YQ: +25.2%, $p = 0.034$, 5-week window), and L'Ametlla de Mar (UA: +3.4%, $p = 0.024$, 16-week window). The remaining two, Arenys de Mar (WT: +18.9%, $p = 0.476$) and Palamós (YP: +5.8%, $p = 0.084$), showed positive point estimates but did not reach significance; these should be read as providing no strong evidence of an effect in either direction, rather than as confirmed positive responses, and are retained

Table 1

Optimal precipitation windows at the optimal port-meteorological stations combination: effect sizes, significance levels, and integration windows for nine fishing grounds. NS $p \geq 0.05$. q(BH) is the Benjamini–Hochberg FDR-adjusted significance across this 9-test family ($\alpha = 0.05$); q(BH)-sig indicates significance is retained after correction.

Port Name	XEMA Station	Effect (% per 10 mm)	p-value	Significance	q(BH)	Window (weeks)
La Ràpita	UW	+60.5	<0.0001	***	<0.0001	5
L'Ametlla de Mar	UA	+3.4	0.0244	*	0.037	16
Tarragona	XE	−10.9	0.0018	**	0.004	18
Vilanova i la Geltrú	XU	+88.4	0.0003	***	0.001	2
Barcelona	YQ	+25.2	0.0338	*	0.043	5
Arenys de Mar	WT	+18.9	0.4759	NS	0.476	4
Blanes	WT	−37.1	<0.0001	***	<0.0001	5
Palamós	YP	+5.8	0.0837	NS	0.094	14
Roses	U2	+99.3	0.0208	*	0.037	2

* Significance: $p < 0.05$.

** Significance: $p < 0.01$.

*** Significance: $p < 0.001$.

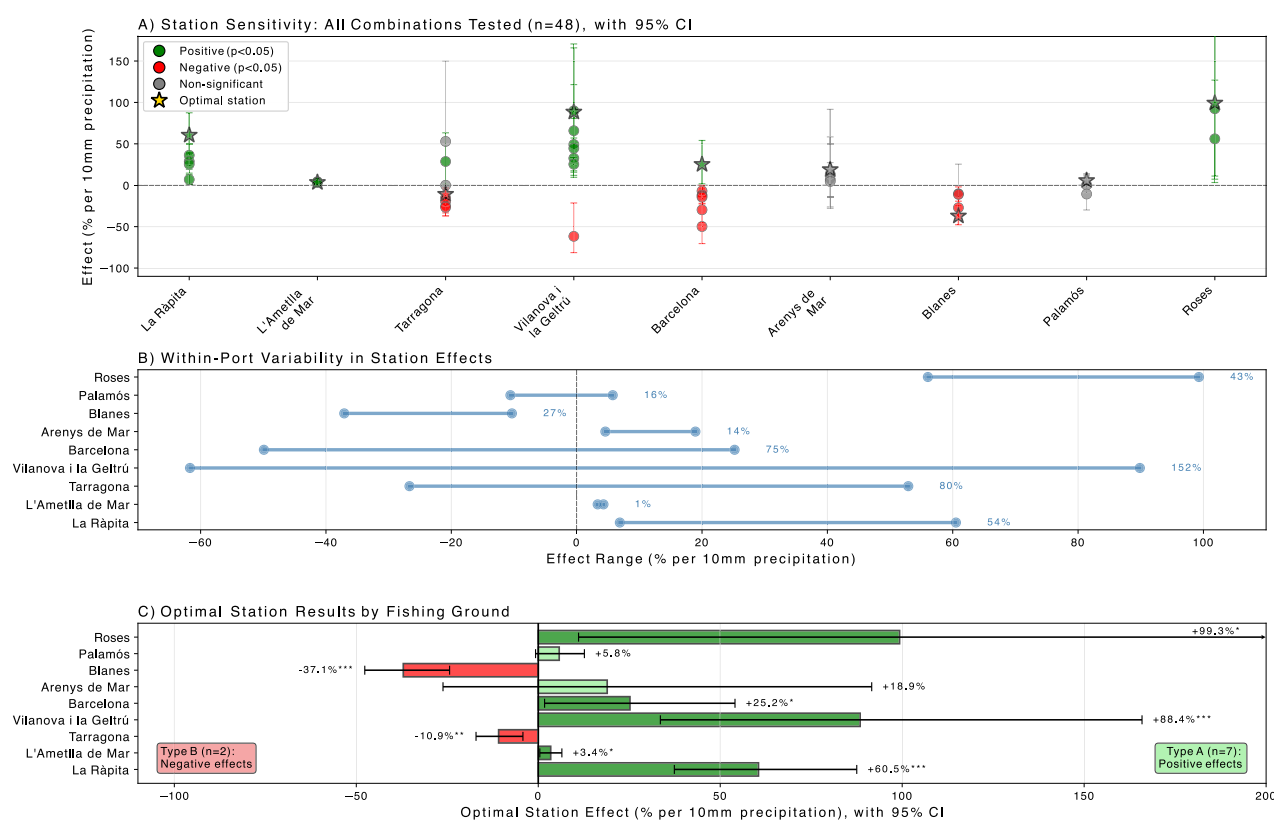


Fig. 2. Station sensitivity analysis for precipitation effects, with 95% confidence intervals. (A) Effect sizes for all station-port combinations (n=50 tests, 9 ports), with 95% Wald confidence intervals shown as vertical error bars. Colors: green = positive significant, red = negative significant, gray = non-significant. Stars mark optimal stations. (B) Within-port effect ranges. (C) Optimal station results by port, with 95% confidence intervals shown as horizontal error bars. Confidence intervals for all 50 tested station-port combinations are reported in full in Supplementary Table S4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in this grouping only for descriptive consistency with the sign of their point estimate.

Type B: Consistent Washout Ports (n = 2)

Two ports showed predominantly negative effects. Blanes demonstrated strong washout (WT: −37.1%, $p < 0.001$, 5-week window), consistent with Tordera River influence (−63.9%). Tarragona showed mixed station signals, with optimal station XE selected to avoid Franco-River washout (−88.5%).

3.3. River discharge effects: Strong washout at hydrologically connected ports

Using the optimal precipitation window for each station identified in Section 3.1, we evaluated river discharge effects at six ports with clear hydrological connectivity to Catalan Water Agency (ACA)-monitored rivers. Across all connected systems, river discharge had consistently negative effects on benthic litter abundance, indicating that increased discharge mobilizes or redistributes litter away from fishing grounds (Supplementary Table 5, Fig. 3). Five of the six ports showed statistically significant washout.

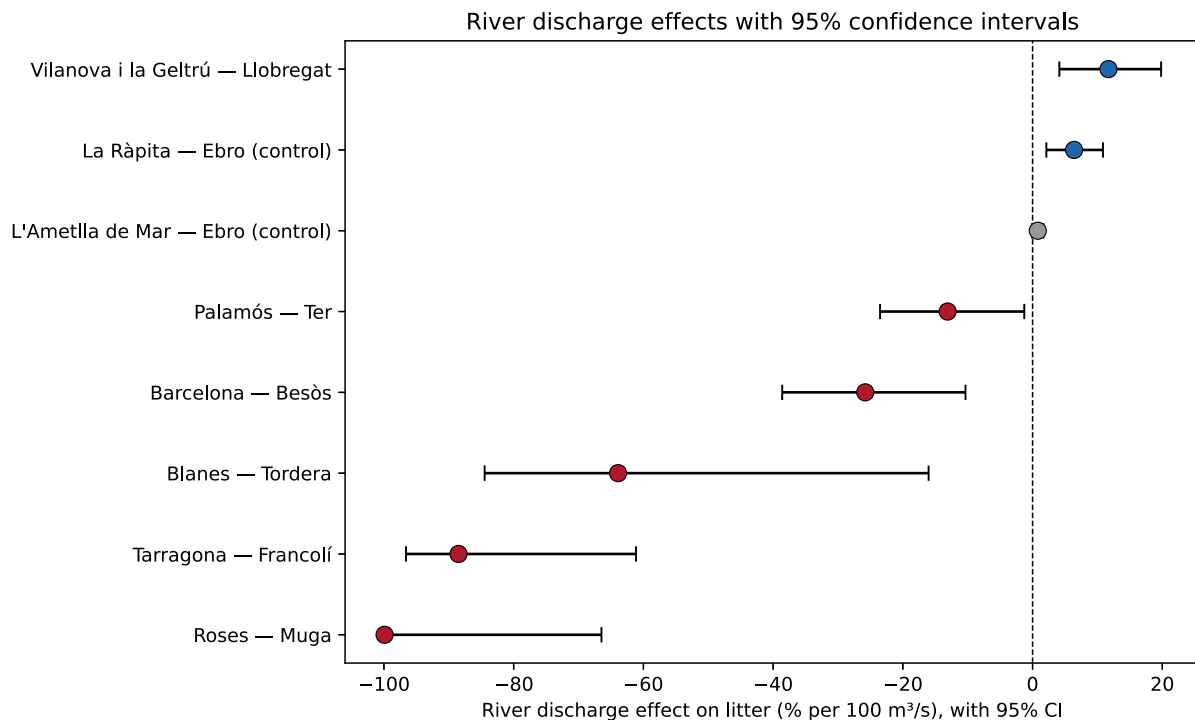


Fig. 3. River discharge effects on benthic litter abundance, with 95% confidence intervals. Points show the estimated percentage change in benthic litter per 100 m³/s discharge increase, for the nine hydrologically tested rivers (six connected systems and three geographic controls, two at the Ebro river, one at the Rhône). Error bars show 95% Wald confidence intervals, computed from each model's coefficient and two-sided *p*-value. Colors indicate direction and significance: blue = significant positive effect (accumulation), red = significant negative effect (washout), gray = not significant (*p* ≥ 0.05). The three geographic controls (La Ràpita and L'Ametlla de Mar on the Ebro, Roses on the Rhône) are included to test the specificity of the modeling approach: L'Ametlla de Mar (Ebro) and Roses (Rhône) controls show non-significant, near-zero effects, while La Ràpita shows a statistically significant but small effect, an order of magnitude smaller than at hydrologically connected rivers (Section 4.6). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Vilanova i la Geltrú represents a unique multi-source accumulation zone, showing both a strong local positive precipitation response (+88.4%, 2-week window) and positive Llobregat river effects (+11.7%, 18-week window, *p* = 0.002), consistent with downstream accumulation from the Barcelona metropolitan area via alongshore transport. Geographic controls at the Ebro river show effect magnitudes small relative to hydrologically connected rivers, though not uniformly non-significant: L'Ametlla de Mar shows a non-significant effect (+0.8%, *p* = 0.071), while La Ràpita shows a statistically significant but small effect (+6.4%, *p* = 0.003), roughly an order of magnitude smaller than effects at connected rivers (Section 4.6). Optimal integration windows ranged from 2–18 weeks, reflecting variable transport and settling dynamics across river-port systems.

The complete landscape of precipitation effects across all tested 2–20 week windows and station-port combinations (Supplementary Figure S3) is shown as a heatmap, revealing three temporal response patterns: Roses shows sharp positive peaks at 2–4 weeks with rapid decay (fast delivery, short residence); Barcelona shows extended responses across 6–14 weeks (multiple competing processes or longer retention); and Vilanova i la Geltrú shows a clear bimodal structure characteristic of multi-source accumulation, with Station XU peaking sharply at 2 weeks (local precipitation response) while the Llobregat river effect builds gradually to 18 weeks (regional transport). Opacity patterns confirm optimal window selections correspond to regions of high statistical significance, demonstrating genuine peaks rather than arbitrary choices.

Effect magnitudes ranged from -13.1% to -99.9% per 100 m³/s (Supplementary Table 5). The strongest washout occurred at Roses (Muga: -99.9%, *p* < 0.001), representing near-complete benthic litter removal, followed by Tarragona (Francolí: -88.5%, *p* < 0.001) and

Blanes (Tordera: -63.9%, *p* = 0.018). Moderate washout was observed at Barcelona (Besòs: -25.8%, *p* = 0.002) and Palamós (Ter: -13.1%, *p* = 0.031). The Rhône geographic control at Roses showed a negligible, non-significant effect (Rhône: ≈ 0%, *p* = 0.176, 18-week window), consistent with the absence of hydrological connectivity expected at over 100 km from the site.

95% confidence intervals for all river discharge effects exclude zero for all hydrologically connected rivers except the weaker Palamós–Ter effect, whose interval (-23.5% to -1.3%) remains entirely negative despite its width. Both Ebro river controls show confidence intervals that are either centered near zero or only marginally exclude it (La Ràpita: 2.1% to 10.8%; L'Ametlla de Mar: -0.1% to 1.7%), consistent with the much smaller effect magnitudes expected at these geographically shielded control sites. The Rhône control's interval is likewise centered on zero, consistent with its non-significant result. Full per-river effect sizes, standard errors, and BH-adjusted significance are reported in Supplementary Table 5.

Following Benjamini–Hochberg correction across this 9-test family, seven of nine river discharge effects retain significance (all except the L'Ametlla de Mar–Ebro and Roses–Rhône geographic controls, both of which were expected to be non-significant). This includes the La Ràpita–Ebro control, which is nominally significant but weak in magnitude (+6.4%) relative to hydrologically connected rivers, and is discussed further in Section 4.6.

3.4. Litter type-specific responses

Partitioning litter into light-urban, heavy-urban, and heavy-industrial categories substantially reduced sample size within each subgroup (from *n*=236 total hauls to as few as 23–31 per port-category combination), and the results below should be read as exploratory rather than

definitive; only 2 of 27 port-level tests and a further 4 of 24 river-level tests reached significance (Section 4.4 discusses statistical power in this subdivided analysis in detail). Light-urban litter showed a significant effect only at Barcelona (+3.6%, $p = 0.010$). Heavy-urban litter showed no significant effects (0/9 ports, all $p > 0.05$). Heavy-industrial litter showed significance only at Arenys de Mar (+6.6%, $p = 0.032$).

River discharge analysis by litter type was similarly constrained by sample size and is likewise exploratory. Light-urban litter showed significant washout at 2 of 8 rivers (Blanes-Tordera: -89.1%, $p = 0.024$; Roses-Muga: -96.9%, $p = 0.043$); geographic controls at the Ebro (La Ràpita and L'Ametlla: $|\beta_1| < 0.0002$, both $p > 0.16$) were consistent with methodological specificity, though a single non-significant control test at this sample size cannot rule out spurious null results on its own. Heavy-urban and industrial categories showed no significant effects at hydrologically connected rivers (0/8 each), though heavy-urban controls unexpectedly achieved significance (La Ràpita: -0.9%, $p = 0.021$; L'Ametlla: +2.8%, $p = 0.022$), suggesting marginal Ebro influence on dense materials despite geographic barriers. Type-specific river analyses remain underpowered and require substantially larger datasets for robust conclusions.

4. Discussion

4.1. Testing hypotheses on land-to-sea litter transport

Our systematic analysis of 50 successful model fits across nine fishing grounds reveals how precipitation and river discharge are associated with benthic marine litter. Contrary to hypothesis 1, five of six hydrologically connected ports showed negative river discharge effects (-13.1% to -99.9%, Supplementary Table 5), contradicting assumptions that rivers deliver litter to nearby beaches (Stagličić et al., 2025) or benthic grounds (Cau et al., 2024; Blanco et al., 2025; Roebroek et al., 2025); rivers predominantly mobilized litter offshore or alongshore instead. The sole exception, Vilanova i la Geltrú (Llobregat: +11.7%), shows that river effects depend on spatial relationships between river mouths, trawling grounds, and coastal circulation, and that riverine inputs do not universally accumulate at benthic fishing grounds.

Urban precipitation showed the predicted spatial restriction (H2) (Blanco et al., 2025). Vilanova i la Geltrú stations ranged from -61.7% to +88.4% depending on watershed characteristics (Fig. 2), variability far exceeding between-port river effects. This pattern is consistent with spatially restricted urban stormwater inputs, of which CSO activation is one plausible contributor, though our precipitation-based proxy cannot isolate CSO discharge from other storm-associated urban runoff.

Temporal signatures provided partial support for Hypothesis 3. Positive precipitation-associated effects spanned 2–16 weeks (median 5 weeks, 5 ports), with 4 of 5 clustering at 2–5 weeks, while river discharge effects spanned 12–18 weeks (four ports) (Supplementary Figure S2). At Vilanova i la Geltrú where the local positive response (2 weeks) and regional river transport (18 weeks) operate at the same location, this represents a 9-fold difference consistent with a distinction between rapid urban runoff and slower river-mediated processes. L'Ametlla de Mar (16 weeks) is a notable exception falling within the river-timescale range. To our knowledge, this represents the first systematic quantification of a distinct temporal correlation structure for urban precipitation versus river pathways to benthic litter; the rapid urban timescale is consistent with surface plastic dynamics where concentrations peak ~9 days post-discharge with subsequent sinking (Biancardi et al., 2026). The bimodal distribution across all ports is consistent with the hypothesis that mechanistically distinct pathways operate at different temporal scales; however, as discussed in Section 4.7, these windows are statistical optima derived from AIC-based model selection and have not been independently validated against physical transport measurements. Attributing the rapid pathway specifically to CSOs (rather than general urban runoff), and treating either timescale

as a directly measured transport time, would require hydrodynamic modeling, particle-tracking, or in-situ transport data beyond the scope of this study.

Source geometry predictions (H4) proved partially correct. Rivers influenced broader coastal stretches as expected, but generated removal rather than accumulation signals. Urban precipitation effects were spatially localized, requiring careful station selection. Spatial extent emerged from interactions among source type, hydrodynamic forcing, and coastal configuration (Supplementary Figure S4), consistent with Mediterranean studies linking bathymetry, circulation, and rivers to litter distribution (Ramirez-Llodra et al., 2013).

4.2. Station selection is critical: Beyond nearest-neighbor approaches

Systematic testing of 54 fishing ground-meteorological station combinations revealed dramatic precipitation effect variation (-37.1% to +99.3% per 10 mm, Table 1) depending on meteorological station choice. This heterogeneity is consistent with genuine hydrological connectivity differences, though we note that station selection criteria and their potential for bias are addressed explicitly in Section 4.7.

Multi-station testing (Supplementary Material Table 2) reveals lessons challenging conventional assumptions: geographic proximity does not guarantee hydrological connectivity. Vilanova i la Geltrú's Station YR, despite proximity, showed strong negative effects (-61%) from local Foix river washout, while the mechanistically motivated Station XU yielded the strongest positive effect (+88.4%, Table 1). This > 150-percentage-point range demonstrates that nearest-neighbor selection can fundamentally mischaracterize hydrological influences.

Barcelona illustrates how station testing resolves apparent contradictions. Most stations showed negative effects (7/9), while the optimal urban-core station (YQ) showed positive effects (+25.2%, surviving Benjamini-Hochberg correction narrowly at $q=0.043$; Section 4.7), a pattern consistent with urban stormwater delivery (Blanco et al., 2025). River-influenced stations capture Besòs washout; urban-core stations capture a signal consistent with local urban runoff delivery. Without multiple-station testing, Barcelona's overall precipitation response would likely be misclassified, though given the narrower statistical margin at this port, we treat this result with somewhat more caution than the other Type A ports.

Multiple-station testing proved essential at ports with heterogeneous signals. Single-station studies would yield conclusions dependent on arbitrary selection. Systematic testing with a priori hydrological and infrastructural criteria (watershed position, proximity to documented discharge points, data completeness; Section 2.3) helped ensure that reported station choices reflected plausible hydrological connectivity rather than geographic proximity alone; the full multi-station distribution is reported in Supplementary Table 4 as a sensitivity check on this selection.

Several ports (La Ràpita, Roses) lie in sheltered bays yet trawl in adjacent open waters, affecting signal detectability (Carreton et al., 2025). La Ràpita shows a signal consistent with urban runoff transport from sheltered bays to open grounds when shielded from rivers (+60.5%). Roses demonstrates that a sheltered configuration can produce the strongest positive precipitation response in the study (+99.3%) despite exposed trawling, yet also experiences extreme Muga washout (-99.9%). "Sheltered" versus "exposed" refers to net effect rather than geographic configuration.

4.3. The Vilanova i la Geltrú accumulation zone: A multi-source hotspot

Vilanova i la Geltrú emerges as a unique accumulation hotspot where multiple litter pathways appear to converge. This port exhibits both the strongest precipitation effect (+88.4%, 2-week window, Station XU, $p = 0.0003$) and the only positive river discharge effect (+11.7%, 18-week window, Llobregat, $p = 0.002$). Its geographic position ~35 km downstream from the Llobregat river mouth and 40 km

southwest of Barcelona is plausibly relevant to understanding this exceptional accumulation (Balcells et al., 2023).

Southward coastal circulation could transport litter from Barcelona to Vilanova i la Geltrú's sheltered grounds (Martínez et al., 2024). Barcelona's urban stormwater network, of which CSOs are one component, is a plausible source delivering litter via coastal currents, while the Llobregat river mobilizes debris transported alongshore (Liste et al., 2014; Gade and Barale, 2008). Unlike other ports where the positive urban precipitation response competes with river washout, here they appear to reinforce each other. The 9-fold difference in statistically optimal windows (2 weeks local, 18 weeks river) is consistent with independent processes contributing to the same deposition zone, though, as elsewhere in this study, these windows are correlation optima rather than measured transport times (Section 4.7), and we cannot confirm from precipitation data alone that CSO discharge specifically, rather than general stormwater runoff, is the local driver.

Station UK provided an additional data point along the same gradient already noted in Section 4.2, showing a weak, non-significant effect (+29%, NS) between Station XU's strong positive signal and Station YR's negative washout, reinforcing that effect magnitude tracks hydrological positioning rather than geographic proximity.

This convergence carries provisional management implications given the mechanistic uncertainty discussed above: Vilanova i la Geltrú's benthic litter problem is unlikely to be solved through local interventions alone, since the port appears to receive litter from both its own urban stormwater infrastructure and the Llobregat system draining the Barcelona metropolitan area, illustrating that impacted sites may be geographically distant from litter origin points. Barcelona's metropolitan area (> 3M inhabitants) is among the western Mediterranean's most populated, where despite treatment infrastructure, large coastal cities discharge considerable garbage (UNEP/MAP, 2015).

4.4. Rapid precipitation-to-accumulation correlation: A 4-week modal window

The predominance of 4-week optimal windows across the full 50-combination station-sensitivity panel (57.1% of stations; Section 2.3.2, Supplementary Table S4) is consistent with most litter reaching benthic accumulation within one month of precipitation events, suggesting remarkably rapid connectivity between terrestrial sources and seafloor deposition, though as noted in Section 4.7 these are statistically optimal correlation lags rather than directly measured transit times. This 4-week mode describes the broader station-sensitivity panel and is distinct from the 2–16-week range of optimal windows among the nine primary per-port results (Section 3.1). This timescale is nonetheless broadly consistent with storm-driven transport mechanisms documented in other coastal systems, where severe storms remobilize and redistribute marine debris from shallow to deep waters (Sanchez-Vidal et al., 2012), and coastal trapped waves during hurricanes transport debris 150%–250% farther than under normal conditions (Brunner and Lwiza, 2019). Although our Mediterranean study region experiences less extreme storms than hurricane-prone areas, precipitation events plausibly generate sufficient hydrodynamic forcing to deliver urban-sourced litter, possibly including CSO discharge, to fishing grounds within weeks.

This rapid correlation window carries potentially important, hypothesis-level management implications: interventions targeting urban stormwater infrastructure could plausibly yield detectable reductions in benthic litter within one to two months, enabling relatively quick assessment of management effectiveness, though confirming this would require paired monitoring of infrastructure changes, water-column transport, and benthic litter, which was beyond the scope of this study. It would also complicate interpretation of longer-term patterns: benthic litter surveys would primarily reflect precipitation from the preceding 1 to 4 months (spanning the 2–16 week range of optimal positive-precipitation windows reported in Section 3.1) rather

than long-term climate trends or gradual changes in terrestrial sources. Inter-annual variability in observed litter abundance may therefore represent recent weather fluctuations more than systematic shifts in litter generation or disposal practices, requiring careful statistical treatment to distinguish genuine trends from hydrological noise.

The temporal patterns also reveal an asymmetry between the statistical signatures of accumulation and removal. Negative effects associated with river washout showed even faster optimal windows (72% at 4 weeks) than positive precipitation-associated effects (47% at 4 weeks), consistent with the hypothesis that river-mobilized removal acts rapidly through hydraulic forcing while urban-sourced litter may accumulate gradually through multiple smaller precipitation events. This is consistent with litter removal operating more efficiently than delivery, if these statistical windows do track physical transport time: rivers could clear trawling grounds quickly during discharge events, whereas urban stormwater inputs may require repeated storms to build up detectable accumulation; this interpretation remains to be tested against direct transport data.

Our 4-week statistically optimal window is broadly compatible with independent evidence from floating plastic dynamics: Biancardi et al. (2026) tracked surface plastic windrows via satellite in the NW Mediterranean, finding concentrations peak ~9 days post-discharge, with 31% subsequently sinking. This rapid surface transport and progressive sinking is broadly consistent with our ~4-week finding, though the two studies used different methods (satellite-tracked windrows versus benthic trawl correlation) and the comparison is suggestive rather than confirmatory. The 31% sinking fraction reported by Biancardi et al. (2026) suggests that most plastic remains afloat or strands on shorelines rather than accumulating on the seafloor; this may help explain why our light-urban litter analysis, dominated by buoyant plastics, showed weaker and less consistent precipitation effects than total litter across most ports (Section 3.4), as much of the plastic debris from urban sources likely bypasses benthic deposition entirely.

4.5. Litter type heterogeneity: Sample size challenges

Partitioning our 236-haul dataset into 9 ports and 3 litter categories severely limited statistical power, producing only 2 significant effects from 27 tests (Section 3.4; Supplementary Material table 3), though these sparse findings hint at patterns that may emerge with larger datasets. Barcelona's urban core station showed the only significant light-urban litter effect (+3.6%, $p = 0.010$), an 85% reduction in magnitude compared to total litter at the same location (+25.2%); Arenys de Mar provided the second significant result, for industrial litter (+6.6%, $p = 0.032$).

Dense materials (glass, metal, rubber) showed no significant responses (0/9 ports), likely reflecting rapid settling, limited transport, or insufficient statistical power.

Effect magnitude reduction when partitioning by type primarily reflects statistical power limitations. Barcelona's total litter effect (+25.2%) exceeds its light-urban effect (+3.6%) by 7-fold. Regional data show abundant hygienic products near Barcelona (Balcells et al., 2023), items commonly associated with sewer-derived inputs that absorb water and sink readily, unlike buoyant packaging (31% sinking fraction, Biancardi et al. (2026)). This may help explain why total litter showed a strong positive precipitation response (7/9 ports) while type-specific analyses lacked power; it does not, on its own, confirm CSO origin for these items.

The contrast between total litter (7/9 significant) and type-specific effects (2/27 significant) demonstrates order-of-magnitude power improvements through aggregation. Type-specific analyses likely require 5–10 times larger datasets for comparable detection, with current findings serving as suggestive indicators.

River discharge effects by litter type showed similarly limited statistical power, with light-urban litter providing the only interpretable pattern. Two of eight rivers showed significant light-urban washout

(Blanes-Tordera: -89.1% , $p = 0.024$; Roses-Muga: -96.9% , $p = 0.043$), consistent with buoyant plastic mobilization during high discharge. Geographic controls at the Ebro (La Ràpita and L'Ametlla de Mar: $|\beta| < 0.0002$, both $p > 0.16$) are consistent with this pattern reflecting genuine hydrological specificity rather than a general artifact, though, as with the total-litter analysis (Section 3.4), a single non-significant control test at this sample size cannot rule out a spurious null result on its own. Heavy-urban and industrial categories showed no significant effects at hydrologically connected rivers (0/8 each), though heavy-urban controls unexpectedly achieved significance (La Ràpita: -0.9% , $p = 0.021$; L'Ametlla: $+2.8\%$, $p = 0.022$). This anomaly suggests either marginal Ebro influence on dense materials via mechanisms distinct from those affecting total litter, or statistical artifacts in underpowered analyses; a marine-based source (e.g., maritime traffic or fishing activity, rather than land-based river input) cannot be excluded with the available data and would be equally consistent with this pattern. Overall, river discharge effects by litter type remain underpowered and inconclusive, requiring substantially larger datasets.

4.6. Geographic controls strengthen causal inference

To evaluate whether our modeling framework correctly distinguishes true hydrological connectivity from spurious correlations, we tested the Ebro river at two southern fishing grounds where minimal influence was expected based on geography: La Ràpita (located behind the Ebro Delta) and L'Ametlla de Mar (>40 km from the river mouth). Despite the Ebro's large size (drainage area $85,530 \text{ km}^2$) and proximity to these ports ($\sim 20\text{--}40$ km), observed effects were small in magnitude at both sites (La Ràpita: $+6.4\%$, $p = 0.003$; L'Ametlla de Mar: $+0.8\%$, $p = 0.071$, Supplementary Table 5). We note explicitly that only L'Ametlla de Mar was non-significant; La Ràpita's control result is itself significant, with a 95% CI (2.1% to 10.8%; Supplementary Table 4) excluding zero. A significant control result means this approach provides only partial, not complete, validation.

First, significance and magnitude are distinct: its effect ($+6.4\%$ per $100 \text{ m}^3/\text{s}$) is $\sim 10\text{--}15$ times smaller than the strongest washout systems (Francolí: -88.5% , Tordera: -63.9%). This gap is not uniform across all connected rivers, however: the weaker or same-direction effects at Llobregat ($+11.7\%$) and Palamós-Ter (-13.1%) are within a factor of two of La Ràpita's magnitude, so "small relative to connected rivers" should be read as small relative to the strongest signals rather than as a blanket comparison. La Ràpita's tight interval reflects large sample size ($n=27$) and low residual variance rather than a practically important signal; we do not treat it as evidence against the broader pattern. Second, several non-exclusive mechanisms could plausibly produce a small residual signal at La Ràpita but not the more distant L'Ametlla de Mar: limited alongshore transport past the delta under some current conditions; shared regional precipitation patterns correlating with both Ebro discharge and local litter dynamics if lag structures only partially overlap; or a genuine but minor hydrological connection not fully blocked by the delta's geomorphology. Distinguishing between these would require targeted hydrodynamic or tracer-based investigation beyond this study's scope.

The mechanisms producing these small-to-negligible effects remain otherwise uncertain: the Ebro Delta's extensive wetlands may retain river-borne litter before it reaches fishing grounds; the wide continental shelf may transport river-delivered litter beyond trawling depths to offshore submarine canyons, bypassing sampled grounds entirely; or dominant coastal currents may disperse Ebro-sourced litter alongshore away from both ports. For total litter, the contrast between small effects at these geographically distant or shielded locations and much larger effects at connected sites supports the interpretation that our modeling approach primarily captures genuine hydrological pathways, though La Ràpita's significant result indicates this validation is partial rather than complete. Type-specific analyses revealed further limitations: heavy-urban geographic controls achieved significance despite geographic

barriers, suggesting either category-specific transport mechanisms or insufficient power when data are subdivided by material type.

For future investigations, the inclusion of negative control locations is recommended to empirically test modeling approaches. Our results indicate that geographic controls perform well for total litter but may be inadequate for type-specific analyses where reduced sample sizes yield marginal effects at sites expected to show null results.

4.7. Study limitations: Proxy variables and statistical inference

A central limitation is that precipitation was used as a proxy for urban stormwater activation, including but not limited to CSO events; we did not directly measure CSO discharge volumes, activation timing, or water-column litter concentrations. The reported precipitation-litter associations at urban ports are therefore consistent with, but do not definitively isolate, a CSO-specific mechanism. General stormwater runoff and storm-associated resuspension near urban coastlines remain plausible alternative pathways producing a similar signature. We accordingly favor neutral language ("urban precipitation-associated response") to describe the observed pattern itself, reserving "CSO" for our motivating hypothesis and station-siting rationale, or where the spatial/temporal signatures and known outfall locations (EU UWWTD, 2025) make it the most parsimonious interpretation rather than a confirmed pathway. Direct CSO discharge measurement or water-column litter sampling remains a priority for future work.

A second, related limitation concerns the temporal windows themselves (2–6 weeks for precipitation, 12–18 weeks for river discharge; Sections 4.1 and 4.3), which are statistical optima from AIC comparison across a discrete lag grid (2, 3, 4, 5, 6, 8, 10, 12, 16, and 20 weeks), not independently validated via hydrodynamic modeling, particle-tracking, current measurement, or sediment transport analysis. We cannot rule out that this window structure partly reflects the autocorrelation of the precipitation and discharge time series themselves (the latter integrating catchment-wide precipitation with its own hydrograph lag) rather than litter transport time specifically, nor exclude noise from sparse per-port samples ($\sim 16\text{--}31$ hauls). We therefore present these temporal differences as a robust, reproducible statistical signature consistent with mechanistically distinct transport pathways, rather than direct evidence of transport processes; independent validation via Lagrangian particle-tracking or current-meter deployments, a direction we are actively pursuing, would be needed to confirm whether these windows reflect real transport timescales.

A third limitation concerns station selection: because multi-station testing generates a range of estimates per port, we defined selection criteria (watershed position, discharge proximity, data completeness; Section 2.3) independently of resulting effect sizes, reporting the full multi-station distribution (Supplementary Table 4) as a sensitivity check rather than relying solely on the optimal-station estimate. We nonetheless flag this as requiring caution, since a priori criteria in a heterogeneous coastal environment cannot fully eliminate the risk that some station choices correlate with the effects they were meant to independently identify.

A fourth limitation concerns multiple comparisons. Our primary results (9 port-level effects, Table 1; 9 river discharge effects, Supplementary Table 5) retain their significance classification after Benjamini–Hochberg FDR correction (Section 2.3.2), including the more marginal effects at Roses, L'Ametlla de Mar, and Barcelona. The latter surviving narrowly ($q=0.043$) and warranting additional caution. However, the broader 50-combination station-sensitivity panel (Supplementary Table 4) and 27 litter type-specific tests (Section 3.4) were not subject to family-wise correction, treated instead as exploratory analyses; these, and particularly the 2 of 27 nominally significant type-specific effects, should be read as suggestive patterns for future investigation with larger datasets rather than independently confirmed findings.

4.8. Management implications

Vilanova i la Geltrú's extreme accumulation (+88.4% local precipitation response, +11.7% upstream river) illustrates that downstream coastal communities can bear disproportionate litter burdens from both local and upstream sources (Galimany et al., 2019; Blanco et al., 2025), likely requiring coordinated regional rather than purely local management: local urban stormwater improvements (Vilanova i la Geltrú, ~67,000 population) alongside upstream river management across the Barcelona metropolitan area (~3.2M population). This asymmetry, where downstream communities accumulate litter originating from much larger upstream populations, carries implications for marine litter governance and cost-sharing frameworks. More broadly, coastal transport redistributes litter across administrative boundaries throughout the Mediterranean basin, and achieving GES under the MSFD and Barcelona Convention likely requires coordinated transboundary approaches that reflect oceanic connectivity rather than political geography.

5. Conclusions

Systematic analysis of 54 station-ground combinations across nine Catalan ports (2019–2024) revealed that precipitation and river discharge are associated with fundamentally different patterns in benthic litter accumulation. Contrary to expectations, rivers predominantly removed rather than delivered litter (5 of 6 ports showing washout), while urban precipitation-associated inputs emerged as the primary correlate of litter delivery. Temporal signatures were broadly consistent with mechanistically distinct pathways: positive precipitation-associated effects typically peaked at 2–5 weeks (4 of 5 significant ports) versus 12–18 weeks for rivers, though one port (L'Ametlla de Mar) fell within the slower range. Precipitation served as a proxy for urban stormwater activation, including but not limited to CSO events; direct CSO discharge was not measured (Section 4.7).

Station selection proved critical. Within Vilanova i la Geltrú alone, station choice produced estimates ranging from –62% to +88% per 10 mm precipitation, demonstrating that hydrological connectivity, not geographic proximity, determines precipitation-litter relationships. This spatial heterogeneity enabled classification into two fishing ground types: Type A (n=7, 5 significant), showing a positive precipitation response consistent with urban stormwater delivery, and Type B (n=2), exhibiting river washout.

Precipitation effects spanned extreme ranges (–37% to +99% per 10 mm). Roses exhibited both the strongest positive precipitation response (+99.3%) and the strongest river washout (–99.9%), showing that intense delivery and near-complete removal can coexist; Vilanova i la Geltrú's multi-source hotspot (+88.4% local, +11.7% upstream) further illustrates how local and regional pathways can combine.

These findings provide a quantitative framework for prioritizing interventions, which should be treated as provisional pending direct confirmation of the underlying discharge mechanisms. Fishing grounds can be classified by dominant statistical source, enabling targeted marine litter management strategies: urban stormwater infrastructure improvements for Type A ports, upstream river management for Type B locations, and coordinated regional approaches for multi-source zones. Rapid transport timescales (typically 2–5 weeks, with a broader 2–16 week range across ports) would, if confirmed, enable assessment of intervention effectiveness on monthly to seasonal scales. Type-specific litter analyses revealed insufficient statistical power (2 of 27 tests significant), indicating substantially larger datasets are required for material-specific responses. Direct measurement of CSO discharge and water-column litter transport remains a priority for future work to confirm this mechanism.

CRediT authorship contribution statement

Xavier Garcia: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Conceptualization. **Maik Neukirch:** Writing – review & editing, Validation, Software, Methodology, Formal analysis, Conceptualization. **Jordi Iglesias:** Writing – review & editing, Validation, Methodology, Data curation. **Elisa Berdalet:** Writing – review & editing, Validation, Funding acquisition, Conceptualization. **Joaquim Ballabrera-Poy:** Writing – review & editing, Validation. **Savitri Galiana:** Writing – review & editing, Validation. **Eva Flo:** Writing – review & editing, Validation, Data curation. **Bru Cabús:** Writing – review & editing, Validation. **Jordi Ribera-Altimir:** Writing – review & editing, Validation, Data curation. **Marta Blanco:** Writing – review & editing, Validation, Data curation. **Eve Galimany:** Writing – review & editing, Validation, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Maik Neukirch, Savitri Galiana reports financial support was provided by Horizon Europe. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.envpol.2026.129028>.

Data availability

All data used in this study are public. The webpages for data repositories have been provided in the references. The Python scripts developed for the analysis of Marine Litter and precipitation data, can be found in the open repository https://github.com/XavierGarcia-pfk/Marine_Litter_public.git.

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