

Title

Settling and rising dynamics of river litter

Authors

James Lofty^{1*}, Daniel Valero², Mário J. Franca¹

Affiliations

¹Institute for Water and Environment, Karlsruhe Institute of Technology, Karlsruhe, Germany

²Department of Civil and Environmental Engineering, Imperial College London, London, UK

*Corresponding author. Email: james.lofty@kit.edu

This is a non-peer reviewed preprint submitted to EarthArXiv

Manuscript submitted for publication in Science Advances

Abstract

Global assessments of river litter transport, accumulation, and export to the oceans remain constrained because the particle-scale hydrodynamic variables governing litter are currently unknown. We resolve this by explaining the vertical dynamics of full-scale river litter (including plastic and non-plastic items) in quiescent water through multi-camera, three-dimensional trajectory reconstructions of 1,011 items spanning 24 River-OSPAR categories, representing ~80% of observed riverine litter. Results show that settling and rising velocities span three orders of magnitude (-82.1 to -0.29 cm s⁻¹ and 0.90 to 143.3 cm s⁻¹, respectively), indicating large variability in transport among litter categories. We identify four trajectory regimes – straight vertical, straight oblique, nonlinear vertical, and nonlinear oblique – and establish a regime map based on particle Reynolds number and litter anisotropy, revealing that these regimes emerge from interactions between wake dynamics and litter geometry. Overall, results deliver the missing parameterization required for physics-based transport and vertical distribution models of river litter, with application towards improved sampling strategies and river litter interception devices.

Teaser

Distinct settling and rising dynamics determine how litter is transported through rivers.

INTRODUCTION

Anthropogenic litter, particularly plastic pollution, poses significant consequences for biodiversity¹, water resources², flooding³ and the economy⁴. Rivers function as both conveyors and accumulation zones for litter from land-based sources^{5,6}. Addressing this challenge requires a predictive understanding of where and when litter is mobilized, transported and retained. Yet estimates of riverine litter concentrations, fluxes, and transport behavior remain highly uncertain⁷ and often inconsistent⁸. Advancing predictive capability depends on hydrodynamic models capable of simulating litter movement⁹⁻¹¹. However, hydrodynamic models based on advection-diffusion equations are fundamentally limited by the lack of parameterization of the particle-scale variables that govern litter transport and dispersion; settling and rising velocities, as well as drag coefficients, transverse motions and trajectory dynamics. Without these key variables, litter

transport predictions remain highly uncertain⁸, limiting our ability to identify accumulation zones, quantify riverine plastic fluxes and design effective monitoring and mitigation strategies.

While the settling and rising dynamics are well understood for spheres^{12–14}, cylinders¹⁵ disks^{16,17}, and plates^{18,19}, and extensive datasets exist for the vertical velocities of microplastics (plastics < 5 mm in size)^{20–23}, they remain largely unquantified for highly heterogeneous objects such as riverine litter. The few existing litter experiments typically rely on idealized geometries and limited sample sizes^{24–26}, which do not represent the extreme geometric diversity of real riverine litter²⁷ and are insufficient to explain the inherent variability of litter transport⁹.

Anisotropic particles exhibit diverse behaviors in quiescent waters, including significant lateral drifting motion and oscillatory or chaotic trajectories²⁸. These complex motions cause variability in transport predictions that cannot be explained by a single vertical velocity^{9,29}. For canonical objects, distinct trajectory regimes have been systematically mapped, with clear relationships between wake dynamics (typically characterized by particle Reynolds or Galileo number), density ratio^{12,14}, geometry¹⁵ or dimensionless inertia^{17,30,31}. However, no equivalent framework currently exists for river litter, nor is there a mechanistic explanation of its dynamics, despite their much wider range of physical properties and dimensionless parameters.

To solve these knowledge gaps, we provide a complete, mechanistic description of the settling and rising dynamics of full-scale riverine litter (including plastic and non-plastic items) under quiescent conditions. Combining two large-scale settling facilities (Fig. 1a) and employing a synchronized multi-camera setup, we reconstruct the three-dimensional trajectories (Fig. 1b) of 1,011 fully representative pristine, deformed, and weathered litter items, representing 80% of the most commonly observed River-OSPAR (Oslo and Paris commission) categories globally²⁷. We (i) quantify the empirical bounds of litter settling and rising velocities, together with their drag coefficients; (ii) characterize four distinct trajectory regimes (straight vertical, straight oblique, nonlinear vertical, and nonlinear oblique), (iii) establish a predictive regime map based on particle Reynolds number and litter anisotropy and (iv) provide the missing mechanistic interpretation of litter vertical transport in quiescent water. We thereby resolve the key hydrodynamic parameters required for physics-based litter transport and vertical distribution models.

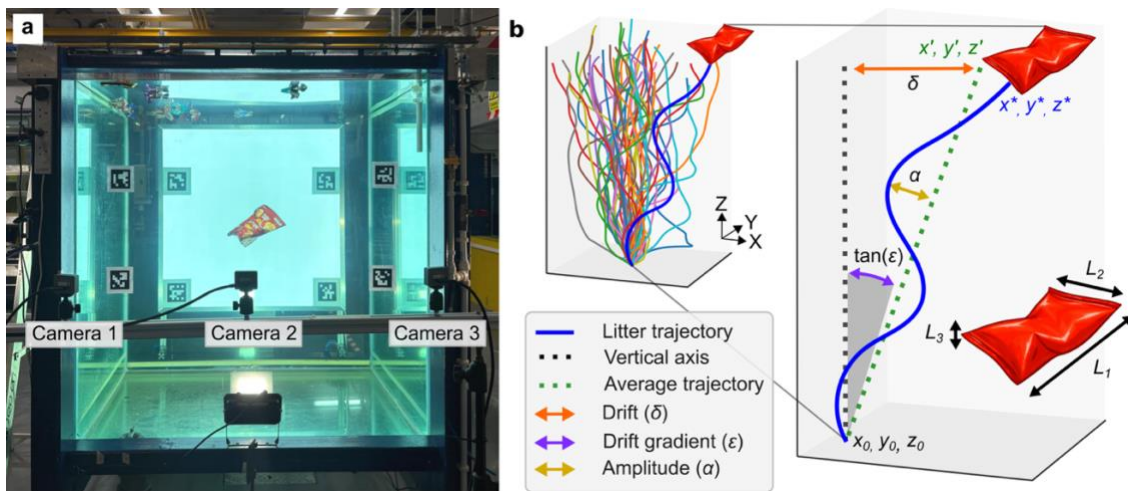


Fig. 1 | Experimental framework for characterizing settling and rising litter. a) Settling tank (Tank 2) and camera configuration enabling three-dimensional trajectory reconstruction with millimeter accuracy. b) Parametrization of trajectory dynamics including drift (δ), drift gradient (ε) and amplitude (α).

RESULTS

Settling and rising velocities of river litter

Vertical velocities ranged between -82.1 and -0.29 cm s^{-1} for rising litter and 0.90 and 143.3 cm s^{-1} for settling litter (Fig. 2a). Vertical velocities were largely explained by their material density ρ_p . Litter composed of intermediate-density materials ($\rho_p \in [0.8, 1.5]$ g cm^{-3}), such as plastics, including soft flexible polyolefins (PO soft), hard rigid polyolefins (PO hard), polyethylene terephthalate (PET) and polystyrene (PS), as well as multilayer materials, paper, and textiles exhibited rising velocities between -0.29 and -21.1 cm s^{-1} and settling velocities between 0.90 and 16.3 cm s^{-1} .

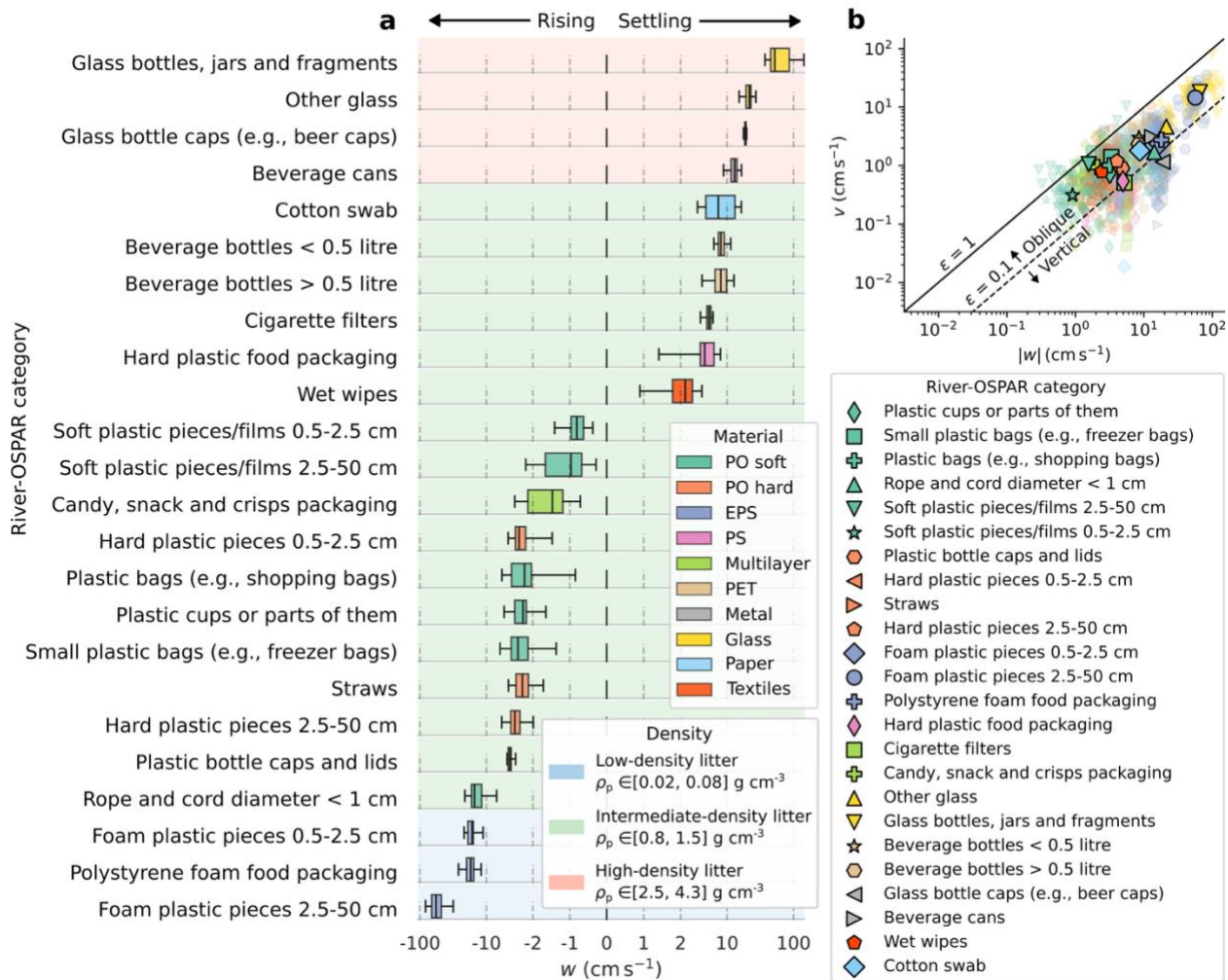


Fig. 2 | Vertical rising and settling velocities of the most persistent River-OSPAR litter categories in river environments. a) Log-scale boxplots of the vertical velocities (w). Box colours denote the material composition of the litter items. Background shading indicates broader density (ρ_p) classes. b) Absolute

vertical velocities plotted against lateral velocities (v), dashed lines indicate the drift gradient $\varepsilon = v/|w|$ delineating vertical ($\varepsilon < 0.1$) and oblique ($\varepsilon > 0.1$) trajectories.

High-density litter composed of glass and metal ($\rho_p \in [2.5, 4.3] \text{ g cm}^{-3}$) displayed the fastest vertical settling velocities between 8.8 and 143.3 cm s^{-1} , while low-density litter composed of expanded polystyrene foam (EPS) ($\rho_p \in [0.02, 0.08] \text{ g cm}^{-3}$) displayed the fastest rising velocities between -7.4 and -82.1 cm s^{-1} . No tested items had material densities between 0.08 and 0.8 g cm^{-3} or between 1.5 and 2.5 g cm^{-3} . Marginal differences were observed between litter items which that were weathered, deformed or pristine (Supplementary Fig. 1).

Drift velocities (v) for litter ranged between 0.002 and 83 cm s^{-1} and tended to increase with the absolute value of the vertical velocity (Fig.2b), indicating that part of the buoyancy force can be transferred to lateral dispersion. To quantify the relative importance of vertical versus lateral velocities, we calculate the drift gradient ($\varepsilon = v/|w|$), which is the rate of horizontal displacement per unit vertical movement, where smaller ε values indicate trajectories dominated by vertical motion with limited horizontal displacement, whereas values approaching 1 indicate vertical and drift velocities of similar magnitudes (i.e. a trajectory at a 45° slope).

Average drift gradients ε across River-OSPAR categories were all below 1, confirming that litter movement was mainly vertically dominated. A small amount of litter items (2%) exhibited ε values greater than 1. Considering a threshold of $\varepsilon = 0.1$ to distinguish straight vertical trajectories from drifting trajectories, we observe that 78% of all litter items exhibited $\varepsilon > 0.1$. These results demonstrate that lateral dispersion is a characteristic feature for most settling and rising litter items, typically exceeding the drift gradients documented for canonical spheres¹², cylinders¹⁵ and steady or oscillating disks^{31,32}.

Drag coefficients C_d and particle Reynolds number ($\text{Re}_p = L_{eff}U/v$) were calculated for each litter item (Fig. 3), based on velocity magnitude $U = \sqrt{w^2 + v^2}$ of the litter item. Because litter items were highly irregular in shape, deformable, and settled in various orientations, an effective, orientation-dependent project area (A_{eff}) and corresponding equivalent projected-area diameter ($L_{eff} = \sqrt{4A_{eff}/\pi}$) were used to calculate Re_p and C_d ³³ (see Methods).

Despite the wide variability in litter size, shape, material and vertical velocity (Fig. 2a), C_d values remained predominantly around 1 across all River-OSPAR categories, with a median of 1.03 and an interquartile range of 0.45–1.72. A detailed statistical breakdown of C_d by River-OSPAR category is provided in Supplementary Table 1.

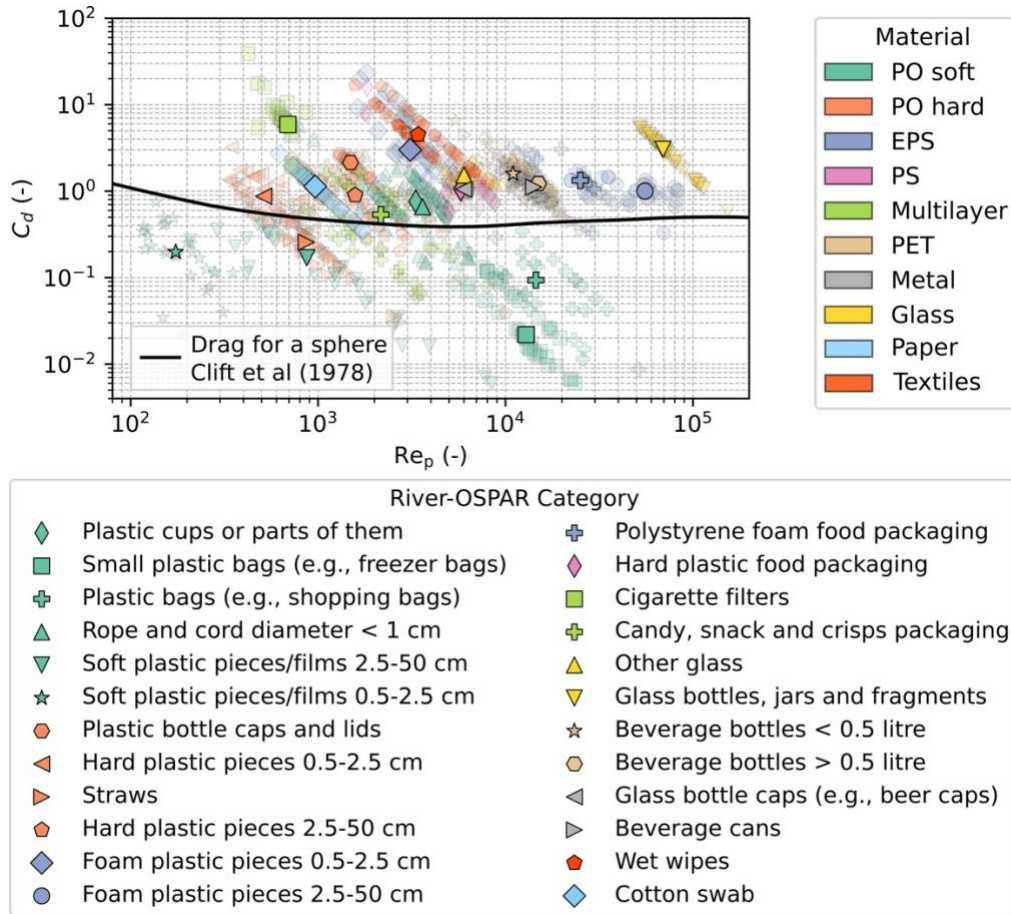


Fig 3. | Drag coefficients for river litter. Calculated drag coefficient (C_d) plotted against the particle Reynolds number (Re_p) for all river litter. Faint markers denote individual litter values, colored by their material composition. Bold markers represent River-OSPAR category median. Black line represents a drag coefficient for a sphere³⁴

Dynamics of river litter

For each of the 1,011 reconstructed trajectories, the litter's drift (δ), defined as the net horizontal displacement along a linear mean trajectory, and amplitude (α), defined as the standard deviation of lateral displacements from the linear mean trajectory were calculated (see Methods). Both amplitude ($\alpha_* = \alpha/L_1$) and drift ($\delta_* = \delta/L_1$) were normalized by the litter's longest length (L_1) and trajectories were classified into four regimes based on the litter's ε and α_* : straight vertical ($\varepsilon < 0.1$, $\alpha_* < 0.05$; Fig. 4a), straight oblique ($\varepsilon > 0.1$, $\alpha_* < 0.05$; Fig. 4b), nonlinear vertical ($\varepsilon < 0.1$, $\alpha_* \geq 0.05$; Fig. 4c), and nonlinear oblique ($\varepsilon > 0.1$, $\alpha_* \geq 0.05$; Fig. 4d).

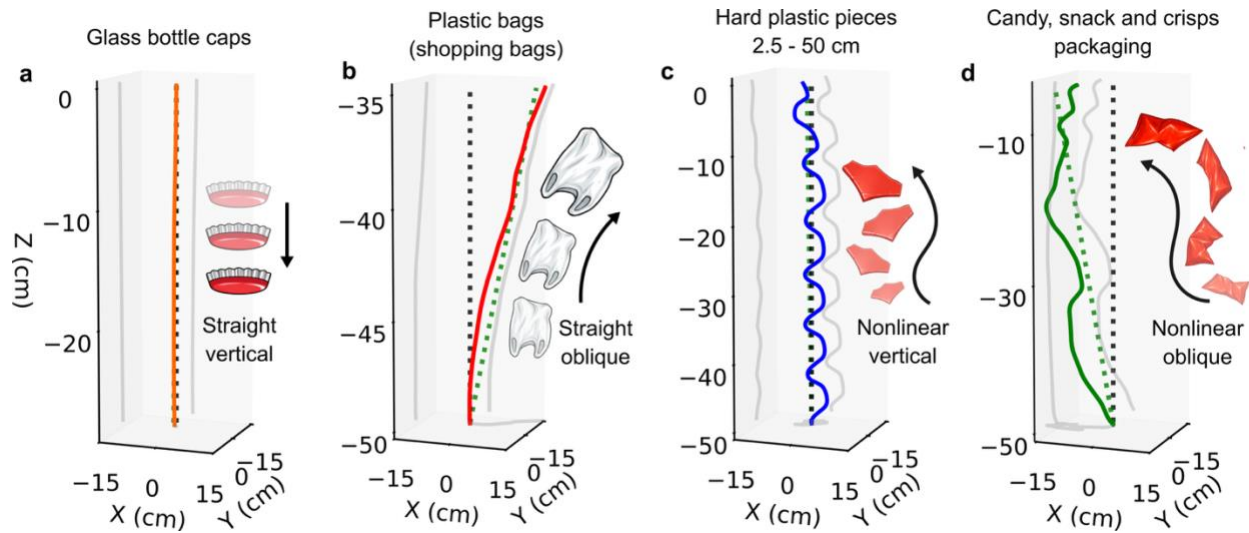


Fig 4. | Settling and rising trajectory regimes of river litter. a) Straight vertical, b) straight oblique, c) nonlinear vertical, d) nonlinear oblique.

The predominant trajectory regime within each River-OSPAR category, defined as the regime accounting for $\geq 50\%$ of trajectories were calculated for each category (Supplementary Fig. 2). Across the 24 River-OSPAR categories, straight oblique trajectories constituted the dominant regime in nine categories (38%). Nonlinear oblique trajectories were the second most dominant regime, occurring in eight categories (33%). In contrast, only two (8%) categories showed a dominant straight vertical regime, whereas one (4%) category exhibited a dominant nonlinear vertical regime. Four categories (17%) were classified as mixed, where no dominant mode was observed.

Results show that normalized litter drift (δ_*) and amplitude (α_*), tended to decrease with increasing particle Reynolds number (Fig. 5). A similar trend is observed when data is plotted against the particle Galileo number (Supplementary Fig. 3), which is commonly used to characterize dynamics of spheres^{12–14} and disks^{16,35}. This indicates that the trajectory dynamics are primarily governed by particle inertia relative to viscous effects, independently of whether they are characterized using the velocity-dependent Reynolds number or the buoyancy-driven Galileo number.

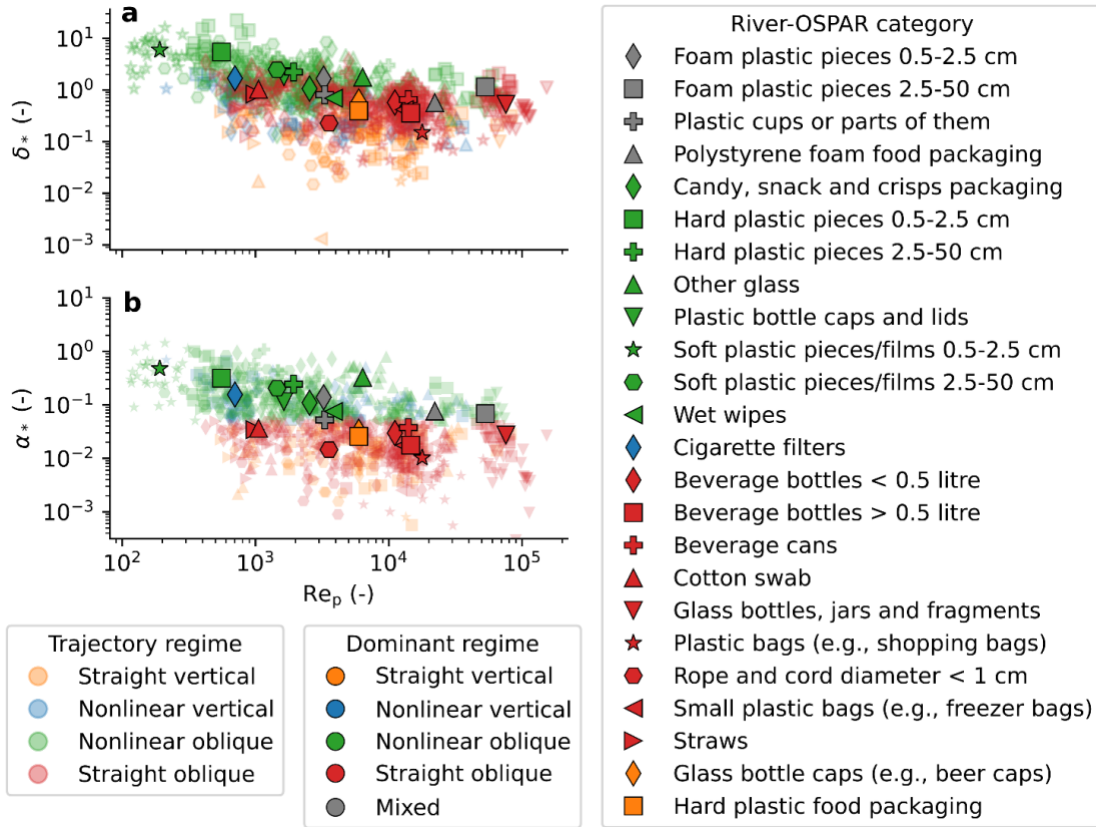


Fig. 5 | Drifting and nonlinear dynamics of river litter. Scatter plots of litter **a)** normalized drift (δ_*) and **b)** amplitude (α_*), as a function of the particle Reynolds number (Re_p). Faint markers denote individual litter trajectories, coloured by their classified trajectory regime (straight vertical, straight oblique, nonlinear vertical and nonlinear oblique). Bold markers represent River-OSPAR category mean, coloured by their dominant regime.

Nonlinear trajectories predominantly occur across intermediate Reynolds numbers ($Re_p \approx 100$ to $3,000$), consistent with the emergence of unsteady laminar-to-transitional wake dynamics. In this regime, coherent vortices that generate lateral forces on the litter body that are shed at scales comparable to the litter scale^{12,28,31}. This drives drift and oscillation amplitudes of litter in the order of $\delta_* \approx 0.3$ to 3 (Fig. 5a) and $\alpha_* \approx 0.05$ to 1 (Fig. 5b). Above $Re_p \approx 3,000$, trajectories become straighter, with δ_* typically falling < 0.3 and α_* frequently < 0.05 . This behaviour is consistent with wake-transition behaviour reported for freely moving bodies²⁸ where, for increasing turbulence, the progressive loss of coherency of the wake-generated vortices reduces effective lateral forces on the object.

These observations extend previously described trajectory regimes to Galileo and Reynolds numbers more than four orders of magnitude higher than earlier work on canonical objects. Unlike studies of spheres or disks, where motion becomes increasingly nonlinear or chaotic as Ga or Re_p increases, our results indicate that litter may reach an asymptotic behavior at very large inertia. For example, steady, straight motion has only been described for spheres at $Ga < 200$ ^{12–14} and for disks at $Re_p < 100$ ^{17,30,31} in prior studies. In contrast, we find that such steady regimes reappear at values nearly two orders of magnitude higher.

Regime map for river litter

To relate the hydrodynamic behavior of litter to its geometry, we first plot the drift gradient (ε) against the particle Reynolds number, where the four identified trajectory regimes become evident (Fig. 6a). Fig. 6b–f then replots the trajectories classified in Fig. 6a onto geometrical descriptors of the litter items, defined by their flatness ($FL = L_3/L_2$) and elongation ($EL = L_2/L_1$) ratios, where L_2 and L_3 represent the intermediate and shortest dimensions of the litter. This allows for trajectory regimes be interpreted through measurable shape parameters.

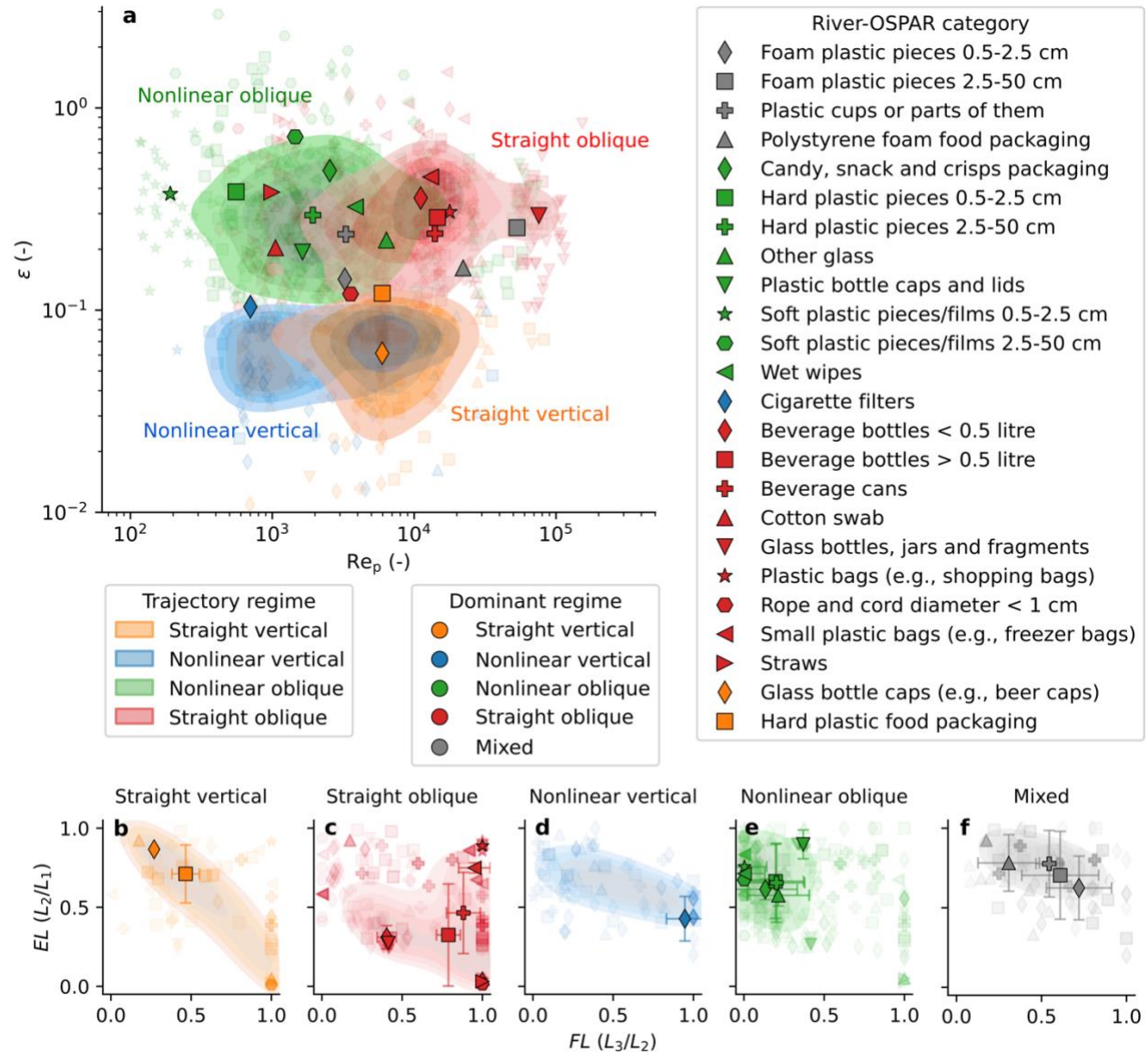


Fig. 6 | Regime map of settling or rising river litter. **a**) Drift gradient (ε) plotted against the particle Reynolds number (Re_p) for all trajectories. Bivariate KDE map (bandwidth = 1) delineates the four trajectory regimes: straight vertical, straight oblique, nonlinear vertical and nonlinear oblique. Faint markers denote individual litter trajectories, coloured by their classified trajectory regime. Bold markers represent category means for each River-OSPAR category. **b – f**) Dominant trajectory regimes in the litter geometry space, defined by flatness ($FL = L_3/L_2$) and elongation ratios ($EL = L_2/L_1$).

Two distinct mechanisms govern the identified trajectory regimes: wake dynamics, which drives the emergence of nonlinear motion, and geometric anisotropy, associated with uneven principal moments of inertia, which governs the oblique motion of litter. At $Re_p < 3,000$ and $\varepsilon > 0.1$, nonlinear oblique trajectories dominate. Items in this regime are primarily small, with low effective mass (e.g., small plastic films and fragments). Due to their small effective mass, these items are highly responsive to laminar-to-transitional wake-induced vortex shedding, producing amplitudes of the order of magnitude of their size (Fig. 5b) and their motion more frequently observed as nonlinear.

All items in the nonlinear oblique region exhibit flat, anisotropic geometries ($FL < 0.4$, $EL = 0.5–0.8$) (Fig. 6e). For such items, inclination relative to the main direction of motion generates asymmetric pressure distributions that yield lift forces, inducing lateral motion³⁶. The combination of wake sensitivity and geometry-driven rotational asymmetry promotes nonlinear oblique trajectories. Although not quantified here, uneven mass distributions may shift a particle's center of mass and alter its moments of inertia, thereby influencing its orientation under hydrodynamic forces³⁷. These changes may produce or amplify lateral motion, as demonstrated for plastic items with heterogeneous biofouling across their surface³⁸.

At $Re_p > 3,000$ and $\varepsilon > 0.1$, trajectories typically transition toward straight oblique motions (Fig. 6a). Litter in this regime are associated with larger litter items with more effective mass (e.g., water-filled plastic bags, plastic bottles, and glass bottles). Their greater effective mass reduces sensitivity to increasingly incoherent wake structures. As a result, these litter items display small amplitudes relative to their size (Fig. 5b), displaying trajectories that are more frequently classified as straight. Despite straight trajectories, these items remain anisotropic in shape, generating lift forces that drive oblique motions (Fig. 6c). Consequently, drift persists but trajectories remain straight. Plastic bags are a notable exception because they deform during motion and adopt geometries that differ from their measured dimension.

For low-density expanded polystyrene (EPS) items, such as foam food packaging and foam fragments, trajectories are more frequently nonlinear or mixed (Fig. 6a), even at particle Reynolds numbers (Re_p) comparable to those of larger litter items that typically follow straight oblique paths (e.g., plastic bags or bottles). Although their particle Reynolds numbers are similar, their masses are up to three orders of magnitude smaller. Consequently, EPS items of a given size experience similar hydrodynamic forcing but respond more rapidly to wake instabilities due to their lower inertia. Their large buoyancy also promotes faster vertical velocities, which further enhances wake instabilities, producing sustained nonlinear movements. This leads to more diverse and variable trajectories, and their overall dominant regime is classified as mixed.

For $\varepsilon < 0.1$, vertical motion dominates and litter trajectories become predominantly straight, independently of Re_p . Litter in this region are generally more isotropic (Fig. 6 b, d), which may be linked to a more symmetric pressure and drag distribution about their center of mass³⁶. This isotropy likely corresponds to more evenly distributed principal moments of inertia, such that hydrodynamic forcing remains balanced and no persistent lateral motion develops. Within this non-oblique regime, two regimes emerge, separated at $Re_p \approx 3,000$. At lower Re_p , litter remains sensitive to laminar-to-transitional wake forcing and therefore exhibits more nonlinear trajectories (e.g. cigarette filters). At higher Re_p , wake production becomes less effective at displacing denser items (e.g., metal bottle caps) or larger rigid litter (e.g., polystyrene packaging), and motion

becomes predominantly straight. The transition between straight and nonlinear behaviour in this region thus reflects differences in wake responsiveness rather than geometric anisotropy.

DISCUSSION

This work resolves the missing particle-scale parameters and mechanistic explanation required for a physical understanding of litter transport and vertical distribution in rivers. We provide, for the first time, settling and rising velocities, drag coefficients, and additional transverse motions caused by lift associated with anisotropic geometries for 1,011 litter items, spanning 24 River-OSPAR categories, which represent approximately 80% of observed riverine litter. The resulting dataset³⁹ provide direct inputs for plastic-transport models^{40,41}, population balance models⁴² and predictions of vertical litter distributions using the Rouse number^{9–11}. Although processes including biofouling and aggregation were not quantified here, applying this dataset within transport models can improve predictions of transport pathways across the diverse properties of riverine litter. How turbulence and other neighboring particles in suspension may affect the settling and rising dynamics of an individual litter item may also require further study.

The three-order-of-magnitude range in vertical velocities and diverse trajectory dynamics show that litter categories cannot be represented by a single transport behavior in rivers. For instance, intermediate-density litter items, such as small plastic films and fragments with low vertical velocities and large drift gradients, would be expected to remain suspended and highly dispersed within the water column. Here, their vertical distribution would be governed primarily by turbulent mixing rather than buoyancy-driven transport. Conversely, high-density glass and metal litter with high settling velocities would be expected to remain concentrated near the bed or largely immobile with limited downstream dispersion. On the other hand, low-density EPS foam litter would be expected to persist on the surface and be rapidly transported downstream.

Combining these results with the hydraulic conditions of a river can enable the quantification of transport regimes, which has direct implications for choosing the appropriate transport modelling frameworks (i.e., bed load or suspended load models), sampling strategies (i.e., selection of representative sampling depths) and interception strategies for river litter (i.e., targeting depths at which devices can most effectively intercept litter). Overall, our results help close the gap in quantifying and describing litter transport, enabling better estimates of concentrations and fluxes, risk assessments and informing targeted solutions to reduce the ecological and human impacts of litter pollution

MATERIALS AND METHODS

Litter items

Litter items tested for the experiments comprise 24 of the 25 most persistent River-OSPAR categories found in rivers and on riverbanks, representing approximately 80% of all riverine litter. This selection is drawn from the dataset compiled by Lofty et al (2026)²⁷, which synthesizes river and riverbank litter observations from 22 study sites across four continents^{43–46}. Only one category ('Other litter') from the top 25 most frequently observed River-OSPAR categories was omitted from experiments because the variability in size, density, and mass within this category was too large to allow meaningful testing.

Tested items consisted of pristine, deformed, and weathered litter and captured the variability typical of river litter (see Supplementary Fig. 4 for validation). Pristine items were newly purchased and tested without damage, whereas deformed items were altered from their original state (e.g., cut fragments or crushed plastic bottles) to replicate common environmental degradation. Weathered items were collected directly from the urban environment, showing visible signs of degradation and were tested in their existing condition. Between 29 and 67 individual litter items per River-OSPAR category were tested, resulting in a total of 1,011 trajectories across all categories. The tested River-OSPAR categories and the ranges of their geometric and material properties are provided in Supplementary Table 2.

Litter physical properties

For each item, the material mass (M), volume (V), and density (ρ_p) were determined to represent litter in dry conditions, while the effective mass (M_{eff}), volume (V_{eff}), and density ($\rho_{p\ eff}$) were calculated to represent litter submerged in water, accounting for water-filled void volumes. The mass of each item was measured to an accuracy of 0.001 g for lighter litter, and 0.1 g for heavier litter. The dry mass was used for non-absorbent litter items and wet mass for absorbent items (i.e. wet wipes and cotton swabs), once at equilibrium absorbance. Material and effective density and volume were determined experimentally where possible using buoyant weighing (Archimedes principles) or a gas pycnometer. A full description of density and volume measurements is provided in the Supplementary Methods.

The longest (L_1), intermediate (L_2) and shortest dimensions (L_3) of the items were measured with a tape measure. When an item's shortest dimension was too small to be measured with a tape measure (< 1 mm), such as for plastic films or wet wipes, L_3 was estimated through the item's volume (i.e. $L_3 = V / (L_1 L_2)$).

Settling tanks and camera setup

Experiments were conducted in two settling tanks. Small litter which demonstrated straight vertical trajectories and had little interactions with the tank walls were tested in a rectangular settling tank (Tank 1), 98 cm in height, 200 cm in length and 57 cm in width at the Theodor Rehbock Hydraulics Laboratory at Karlsruhe Institute of Technology (Germany). Larger litter, which exhibited significant horizontal drift and amplitudes and could have led to wall interactions in Tank 1, were measured in a 128 cm cuboidal settling tank (Tank 2, Fig. 1A) at the Hydrodynamics Laboratory at Imperial College London (United Kingdom). Three Baumer VLXT-81C.I cameras (2/3" CMOS sensor, 2848×2832 px², 60 FPS) were positioned to record litter trajectories in Tank 1, while three OBSBOT Meet 2 cameras (1/2" CMOS sensor, 1980×1080 pixel², 60 FPS) were used in Tank 2. Full description of camera specifications and set up is provided in the Supplementary Methods.

Release protocol

Litter items were released individually into the settling tanks. Negatively buoyant items were released just below the water surface by hand, whereas positively buoyant items were released from the bottom of the tank using a 2.4 m-long grabber. Items were released at random orientations to explicitly capture the full range of settling or rising dynamics of the litter items. Care was taken during each release to minimize external disturbances in the tank that could introduce bias in the initial orientation or motion of the item.

Prior to release, items were gently agitated to remove air bubbles adhering to their surfaces or internal voids and the experiment did not start until free surface disturbances vanished. To improve contrast with the background during image detection, transparent and translucent items were marked using blue or black marker pen, resulting in less than 1% change in item mass⁴⁷. Once released, litter items travelled at least 15 cm through the water column, reaching a stable orientation and motion independent of release conditions before tracking was initiated.

Litter tracking and three-dimensional reconstruction

A bounding box detection routine, using the Python library OpenCV⁴⁸, was used to capture the litter's contour and center-of-mass position per frame from each of the three camera's video sequence, similar to previous studies^{10,38,49}. An ellipse was fitted to the contour in each camera view, with its major axis defining the settling or rising orientation angle (θ). This angle was averaged across the three cameras and over the full vertical trajectory to obtain the ensemble-averaged orientation ($\bar{\theta}$), which was then used to calculate the orientation-dependent projected area as:

$$A_{eff} = L_2(L_3 \cos \bar{\theta} + L_1 \sin \bar{\theta}) \quad (\text{Eq. 1})$$

Because highly irregular and flexible litter items do not settle in a single stable orientation⁹ and therefore present different projected areas, incorporating the orientation-dependent projected area provides a more representative estimate of the drag coefficient³³, which was used in subsequent calculations:

$$C_d = \frac{2|\rho_p - \rho_f|gV}{\rho_f A_{eff} U^2} \quad (\text{Eq. 2})$$

where ρ_f is the fluid density.

The 2D image coordinates of the litter obtained from three cameras were then used to reconstruct the litter's 3D center-of-mass position (x, y, z) in the tank via ray-intersection triangulation, accounting for refraction across the air–glass–water interfaces, following methods by Duinmeijer et al (2019)⁵⁰ and described in full in Valero et al (2022)¹⁰.

Camera extrinsic parameters were calibrated using ArUco markers mounted on the front wall of the tank¹⁰. Reconstruction accuracy was evaluated by comparing the known spatial coordinates of ArUco markers mounted on the front and back walls with their reconstructed positions. Across all experiments reconstruction errors were less than 3 mm in each coordinate direction. This procedure yielded vertical litter trajectories of approximately 35 cm in Tank 1 and 50 cm in the larger Tank 2. A detailed description of the 3D reconstruction algorithm and trajectory smoothing is provided in the Supplementary Methods while an exemplary detection and reconstruction routine is provided in Lofty et al (2026)³⁹

Trajectory characterization

The vertical velocity (w) for each trajectory was calculated for each trajectory as the net vertical displacement divided by the corresponding time interval over the entire trajectory.

$$w = \frac{z_* - z_0}{t_* - t_0} \quad (\text{Eq. 3})$$

where z_0 and z_* are the initial and final vertical positions of the trajectory (Fig. 1 b), and t_0 and t_* are the corresponding times.

To quantify lateral drifting motions, two linear regressions were fitted to the litter trajectory in the $x - z$ and $y - z$ planes using ordinary least squares, treating z as the independent variable. The resulting fits define a linear mean trajectory in three-dimensional space. This provides a consistent reference for quantifying the litter's trajectory dynamics (Fig. 1b). The lateral drift (δ) of each litter item can then be defined as the Euclidean distance between the particle's initial coordinates (x_0, y_0) and the average trajectory's final coordinates (x', y') in the horizontal plane:

$$\delta = \sqrt{(x' - x_0)^2 + (y' - y_0)^2} \quad (\text{Eq. 4})$$

which yields the drift velocity (v):

$$v = \frac{\delta}{t_* - t_0} \quad (\text{Eq. 5})$$

To quantify the litter's nonlinear motion, the amplitude of the trajectory (α) was defined as the standard deviation of lateral displacements between the measured trajectory and the linear regression-based average trajectory (Fig. 1b). This is calculated by projecting the horizontal displacement vector at each vertical position onto the direction perpendicular to the overall drift. Thus, α is a measure of how strongly the trajectory departs from a straight linear path, with larger values indicating greater deviation.

REFERENCES

1. Clark, B. L. *et al.* Global assessment of marine plastic exposure risk for oceanic birds. *Nat. Commun.* **14**, 3665 (2023).
2. MacLeod, M., Arp, H. P. H., Tekman, M. B. & Jahnke, A. The global threat from plastic pollution. *Science (1979)*. **373**, 61–65 (2021).
3. Honingh, D. *et al.* Urban River Water Level Increase Through Plastic Waste Accumulation at a Rack Structure. *Front. Earth Sci. (Lausanne)*. **8**, (2020).
4. Beaumont, N. J. *et al.* Global ecological, social and economic impacts of marine plastic. *Mar. Pollut. Bull.* **142**, 189–195 (2019).
5. Meijer, L. J. J., Emmerik, T. van, Ent, R. van der, Schmidt, C. & Lebreton, L. More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. *Sci. Adv.* **7**, eaaz5803 (2021).
6. van Emmerik, T., Mellink, Y., Hauk, R., Waldschläger, K. & Schreyers, L. Rivers as Plastic Reservoirs. *Frontiers in Water* **3**, 786936 (2022).
7. Vriend, P. *et al.* Uncertainties in Visual Observations of Floating Riverine Plastic. *ACS ES&T Water* **5**, 3920–3928 (2025).
8. González-Fernández, D., Roebroek, C. T. J., Laufkötter, C., Cózar, A. & van Emmerik, T. H. M. Diverging estimates of river plastic input to the ocean. *Nature Reviews Earth & Environment* **2023 4:7** **4**, 424–426 (2023).
9. Lofty, J. *et al.* On the vertical structure of non-buoyant plastics in turbulent transport. *Water Res.* **254**, 121306 (2024).
10. Valero, D., Belay, B. S., Moreno-Rodenas, A., Kramer, M. & Franca, M. J. The key role of surface tension in the transport and quantification of plastic pollution in rivers. *Water Res.* **226**, 119078 (2022).

11. Cowger, W., Gray, A. B., Guiling, J. J., Fong, B. & Waldschläger, K. Concentration Depth Profiles of Microplastic Particles in River Flow and Implications for Surface Sampling. *Environ. Sci. Technol.* **55**, 6032–6041 (2021).
12. Jenny, M., Dušek, J. & Bouchet, G. Instabilities and transition of a sphere falling or ascending freely in a Newtonian fluid. *J. Fluid Mech.* **508**, 201–239 (2004).
13. Raaghav, S. K. R., Poelma, C. & Breugem, W. P. Path instabilities of a freely rising or falling sphere. *International Journal of Multiphase Flow* **153**, 104111 (2022).
14. Cabrera-Booman, F., Plihon, N. & Bourgoin, M. Path instabilities and drag in the settling of single spheres. *International Journal of Multiphase Flow* **171**, 104664 (2024).
15. Toupont, C., Ern, P. & Roig, V. Kinematics and wake of freely falling cylinders at moderate Reynolds numbers. *J. Fluid Mech.* **866**, 82–111 (2019).
16. Auguste, F., Magnaudet, J. & Fabre, D. Falling styles of disks. *J. Fluid Mech.* **719**, 388–405 (2013).
17. Field, S. B., Klaus, M., Moore, M. G. & Nori, F. Chaotic dynamics of falling disks. *Nature* **388**, 252–254 (1997).
18. Smith, E. H. Autorotating wings: an experimental investigation. *J. Fluid Mech.* **50**, 513–534 (1971).
19. Anderson, A., Pesavento, U. & Wang, Z. J. Unsteady aerodynamics of fluttering and tumbling plates. *J. Fluid Mech.* **541**, 65 (2005).
20. Waldschläger, K. & Schüttrumpf, H. Effects of Particle Properties on the Settling and Rise Velocities of Microplastics in Freshwater under Laboratory Conditions. *Environ. Sci. Technol.* **53**, 1958–1966 (2019).
21. Goral, K. D. *et al.* Settling velocity of microplastic particles having regular and irregular shapes. *Environ. Res.* **228**, 115783 (2023).
22. Yu, Z., Yang, G. & Zhang, W. A new model for the terminal settling velocity of microplastics. *Mar. Pollut. Bull.* **176**, 113449 (2022).
23. Khatmullina, L. & Isachenko, I. Settling velocity of microplastic particles of regular shapes. *Mar. Pollut. Bull.* **114**, 871–880 (2017).
24. Kuizenga, B., Van Emmerik, T., Waldschläger, K. & Kooi, M. Will it Float? Rising and Settling Velocities of Common Macroplastic Foils. *ACS ES and T Water* **2**, 975–981 (2022).
25. Born, M. P., Junge, L. V., Brüll, C., Waldschläger, K. & Schüttrumpf, H. Terminal settling and rising velocity prediction of macroplastics: Medical face masks as newly emerged objects of concern. *Science of The Total Environment* **908**, 167922 (2024).
26. Royer, S. J. *et al.* Rise velocity of small polyolefin plastics in a seawater tank exposed to natural conditions in Hawai'i. *Environ. Res. Commun.* **7**, 095018 (2025).
27. Lofty, J., Rebai, D., Valero, D. & Franca, M. J. The Shapes and Sizes of Macroplastics and Other Litter in Rivers. *Environ. Sci. Technol.* <https://doi.org/10.1021/acs.est.5c13126> (2026) doi:10.1021/acs.est.5c13126.
28. Ern, P., Risso, F., Fabre, D. & Magnaudet, J. Wake-Induced Oscillatory Paths of Bodies Freely Rising or Falling in Fluids. *Annu. Rev. Fluid Mech.* **44**, 97–121 (2012).
29. Baker, L. J. & Coletti, F. Experimental investigation of inertial fibres and disks in a turbulent boundary layer. *J. Fluid Mech.* **943**, A27 (2022).
30. Willmarth, W. W., Hawk, N. E. & Harvey, R. L. Steady and Unsteady Motions and Wakes of Freely Falling Disks. *Phys. Fluids* **7**, 197–208 (1964).

31. Stringham, G. E., Simons, D. B., Guy, H. P. & Pecora, W. T. The Behavior of Large Particles Falling in Quiescent Liquids. *US Government Printing Office* (1969).
32. Fernandes, P. C., Risso, F. D., Ern, P. & Magnaudet, J. Oscillatory motion and wake instability of freely rising axisymmetric bodies. *J. Fluid Mech.* **573**, 479–502 (2007).
33. Bagheri, G. & Bonadonna, C. On the drag of freely falling non-spherical particles. *Powder Technol.* **301**, 526–544 (2016).
34. Clift, R., Grace, J. R. & Weber, M. E. Bubbles, Drops, and Particles (Dover Civil and Mechanical Engineering). 380 (1978).
35. Tinklenberg, A., Guala, M. & Coletti, F. Thin disks falling in air. *J. Fluid Mech* **962**, (2023).
36. Mandø, M. & Rosendahl, L. On the motion of non-spherical particles at high Reynolds number. *Powder Technol.* **202**, 1–13 (2010).
37. Huang, W., Liu, H., Wang, F., Wu, J. & Zhang, H. P. Experimental study of a freely falling plate with an inhomogeneous mass distribution. *Phys. Rev. E* **88**, 053008 (2013).
38. Lofty, J., Wilson, C. & Ouro, P. Biofouling changes the settling dynamics of macroplastic plates. *Commun. Earth Environ.* **5**, 750 (2024).
39. Lofty, J. JamesLofty/Settling_rising_litter_dataset: Settling_rising_litter_dataset_v3. <https://doi.org/10.5281/zenodo.23245210> (2026) doi:10.5281/zenodo.23245210.
40. Vallés, P., Morales-Hernández, M. & Roeber, V. Modeling Plastic Transport in Aquatic Environments: the Ebro River case. *Jornada de Jóvenes Investigadores del I3A* **14**, (2026).
41. Petaccia, G. *et al.* Two-dimensional simulation of plastic bottles transport in a urban reach of the Arno River. *Digital Water* **4**, (2026).
42. Shettigar, N. A., Bi, Q. & Toorman, E. Assimilating Size Diversity: Population Balance Equations Applied to the Modeling of Microplastic Transport. *Environ. Sci. Technol.* **58**, 16112–16120 (2024).
43. van Emmerik, T. *et al.* Riverbank macrolitter in the Dutch Rhine–Meuse delta. *Environmental Research Letters* **15**, 104087 (2020).
44. Tramoy, R., Colasse, L., Gasperi, J. & Tassin, B. Plastic debris dataset on the Seine river banks: Plastic pellets, unidentified plastic fragments and plastic sticks are the Top 3 items in a historical accumulation of plastics. *Data Brief* **23**, 103697 (2019).
45. Ballerini, T. *et al.* Plastic pollution on Durance riverbank: First quantification and possible environmental measures to reduce it. *Frontiers in Sustainability* **3**, 866982 (2022).
46. de Lange, S. I. *et al.* Sample size requirements for riverbank macrolitter characterization. *Frontiers in Water* **4**, (2023).
47. Valero, D., Felder, S., Seidel, F., Moreno-Rodenas, A. & Franca, M. J. Low-intrusive colour-enhanced pattern coating of plastics for fluid-mechanics laboratory experiments. *EGU General Assembly* 8159 Preprint at <https://doi.org/10.5194/egusphere-egu24-8159> (2025).
48. Bradski, G. The openCV library. *Dr. Dobb's Journal: Software Tools for the Professional Programmer* **25**, 120–123 (2000).
49. Lofty, J. *et al.* Three-Dimensional Settling Dynamics of Environmental Microplastics. *Environ. Sci. Technol.* <https://doi.org/10.1021/ACS.EST.5C12960> (2026) doi:10.1021/ACS.EST.5C12960.

50. Duinmeijer, S. P. A. *et al.* A simple measuring set-up for the experimental determination of the dynamics of a large particle in the 3D velocity field around a free surface vortex. *Flow Measurement and Instrumentation* **65**, 52–64 (2019).

Acknowledgments

Funding:

JL - Alexander von Humboldt Foundation Research Fellowship

Author contributions:

Conceptualization: JL, DV, MF

Methodology: JL, DV, MF

Investigation: JL

Supervision: DV, MF

Writing—original draft: JL

Writing—review & editing: JL, DV, MF

Competing interests:

No competing interests from all authors

Data, code, and materials availability:

Complete dataset and litter detection and reconstruction codes available at <https://doi.org/10.5281/zenodo.20406725>

Supplementary Materials

Supplementary materials 1

Supplementary Materials for
Settling and rising dynamics of river litter

Lofty, James et al.

*Corresponding author. Email: james.lofty@kit.edu

This PDF file includes:

Supplementary Text
Figs. S1 to S4
Tables S1 to S2

Other Supplementary Materials for this manuscript include the following:

Data S1 to S2

Supplementary Text

Supplementary Methods 1: Determination of litter mass, volume, and material density

The mass (M), volume (V), and material density (ρ_p) of each litter item were determined experimentally where feasible. Item mass was measured using balances with an accuracy of 0.001 g for lighter items and 0.1 g for heavier items. For non-absorbent materials, dry mass was used. For absorbent items (e.g., wet wipes and cotton swabs), mass was measured after the items had reached equilibrium water absorption to reflect their submerged mass during experiments.

The material density and volume for each item were determined using one of three approaches. For small, non-porous items without internal voids (e.g., metal bottle caps), material volume was determined using buoyant weighing. Each item was weighed in air and then while suspended in still water. The difference in apparent weight corresponds to the buoyant force acting on the object and therefore to the weight of the displaced water. From this, the material volume was calculated using Archimedes' principle, and material density was obtained from $\rho_p = M / V$.

For larger litter items that could not be fully immersed (e.g., bottles or large bags), material density was measured using a gas pycnometer. Small cuttings from the litter item were analyzed in the pycnometer to determine the density of the material composing the item. The material volume of the full item was then calculated from the measured mass and the pycnometer-derived density.

For certain items, where neither buoyant weighing nor gas pycnometer was feasible, material density values were obtained from published reference data²⁷, which included litter composed of glass, aluminum, and high-density polyethylene.

Supplementary Methods 2: Calculation of effective volume and effective density

Many litter items contain internal voids that significantly affect their hydrodynamic behaviour. Examples include plastic bottles, plastic bags, and other hollow containers. For such items, the solid material volume represents only a small fraction of the total volume occupied by the item when submerged.

To account for this, items with a defined internal void were assigned an effective volume based on their principal external dimensions, approximated as a cuboid ($V_{void} = L_1 L_2 L_3$), representing the total volume of water displaced by the item. This included plastic bags, glass bottles and plastic bottles. This void volume and its associated displaced water mass were then incorporated into the item's total (effective) volume ($V_{eff} = V + V_{void}$) and mass ($M_{eff} = M + (V_{void} \rho_f)$), from which an effective density ($\rho_{p\,eff}$) was calculated as $\rho_{p\,eff} = M_{eff} / V_{eff}$.

For example, a plastic bag may have a material volume of only $1.33 - 29 \text{ cm}^3$, yet when filled with water and freely suspended in quiescent conditions the bag can occupy between 19,000 and 130,000 cm^3 of water that move coupled with the litter. Should the litter be subject to wake perturbations, both the added mass of water and the litter need to accelerate in response, and therefore this constitutes an increased inertia. Similarly, its effective density approaches that of water, approximately 0.99 g/cm^3 , departing from the lower density of the plastic material alone.

This effective density was used to calculate the Galileo number ($Ga = \frac{\sqrt{|\rho_{p \text{ eff}}/\rho_f - 1|gL_{\text{eff}}^3}}{\nu}$), describing the ratio between gravitational (buoyancy) forces and viscous forces where, ρ_f is the fluid density, g is gravitational acceleration, ν is the kinematic viscosity of the fluid.

Supplementary Methods 3: Camera specifications and setup

Two different setups were used to capture the settling and rising dynamics of litter items and their trajectories from both Tank 1 and Tank 2 (Figure 1A). In Tank 1 (at the Theodor Rehbock Hydraulics Laboratory at Karlsruhe Institute of Technology), cameras were positioned on the same baseline, 101 cm away from outer face of the tank. Cameras were simultaneously triggered via external hardware controlled by Streampix software, enabling synchronized frame matching across all three cameras.

In Tank 2 (at the Hydrodynamics Laboratory at Imperial College London) cameras were positioned on the same baseline, 96 cm away from outer face of the tank (Figure 1A). All three cameras in Tank 2 were triggered simultaneously via computer software. Because frame timing was not perfectly synchronized using the computer software, an external LED flashlight was used to enable consistent cross-camera alignment, achieving synchronization within two frames across all three cameras, similar to methods described in Valero et al (2022)¹⁰.

Supplementary Methods 4: 3D reconstruction algorithm and trajectory smoothing

The synchronized 2D image coordinates of the litter obtained from three cameras were used to reconstruct the litter's 3D centre-of-mass position (x, y, z) in the tank via ray crossing following methods by Duinmeijer et al (2019)⁵⁰ and described in full in Valero et al (2022)¹⁰. Camera intrinsic parameters were calibrated using a chessboard pattern. For each camera, 2D image points were projected into the 3D space as rays, accounting for refraction at the air-glass and glass-water interfaces, for which the litter's depth coordinate (y) was obtained by ray-intersection triangulation. For each time step, 3D positions were computed for all camera pairs. The final coordinates were selected from the pair with the largest parallax angle – typically cameras 1 and 3 (Figure 1A), as this configuration yielded the most stable depth estimates.

To remove noise from the detected coordinates, a spatial filter was first applied to the x and y coordinates using the interquartile range of the detected points. The trajectories were then further refined using Gaussian smoothing to reduce high-frequency noise introduced during the 3D reconstruction process, while preserving the larger-scale litter motion. A cutoff frequency between 0.1 and 1 Hz was applied to all x, y, z coordinates, effectively suppressing small, noisy fluctuations while retaining the dominant motion patterns, thereby allowing the behaviour of the litter to be clearly quantified.

629
630
631

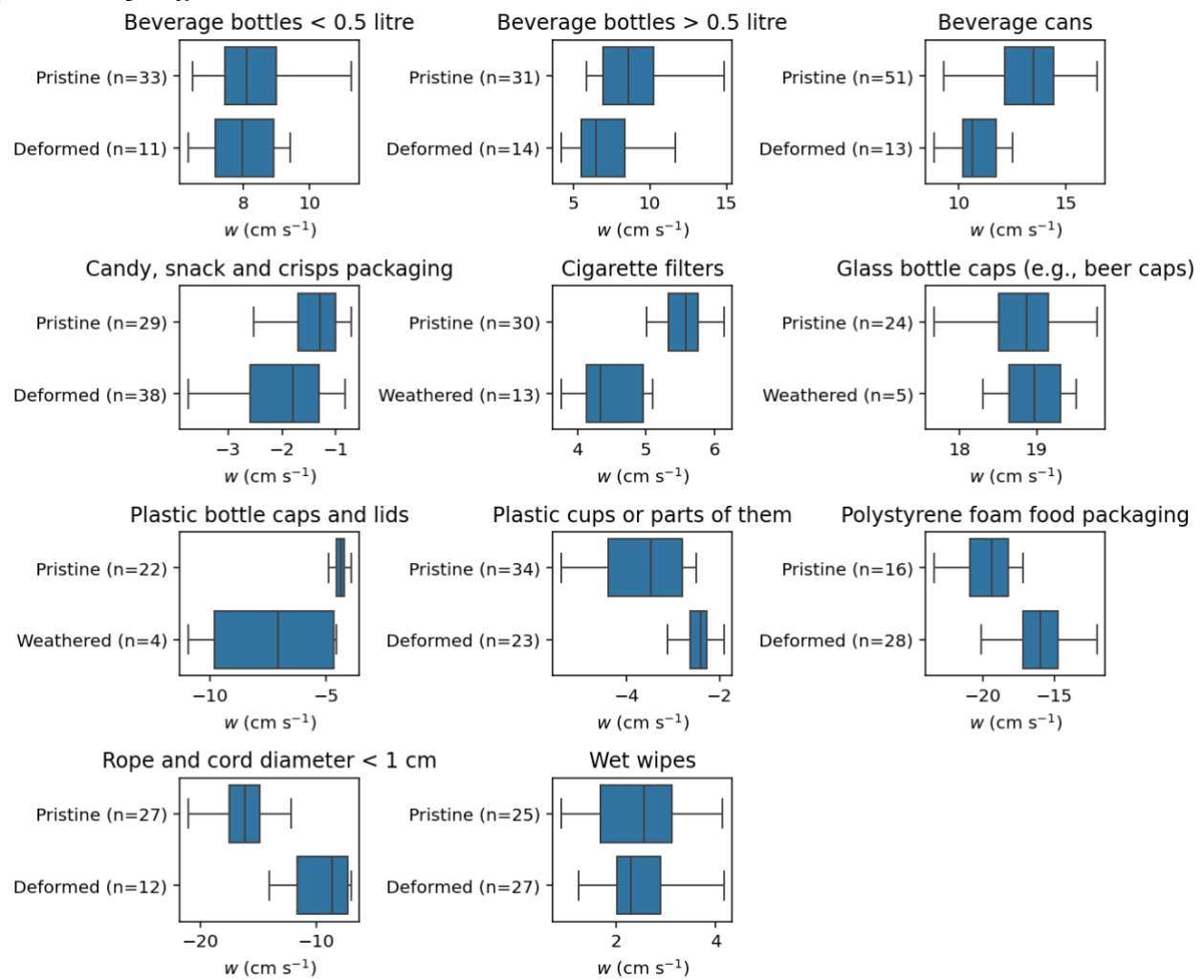


Fig. S1. Settling and rising velocities for the River-OSPAR categories split by their tested state: pristine, weathered or deformed.

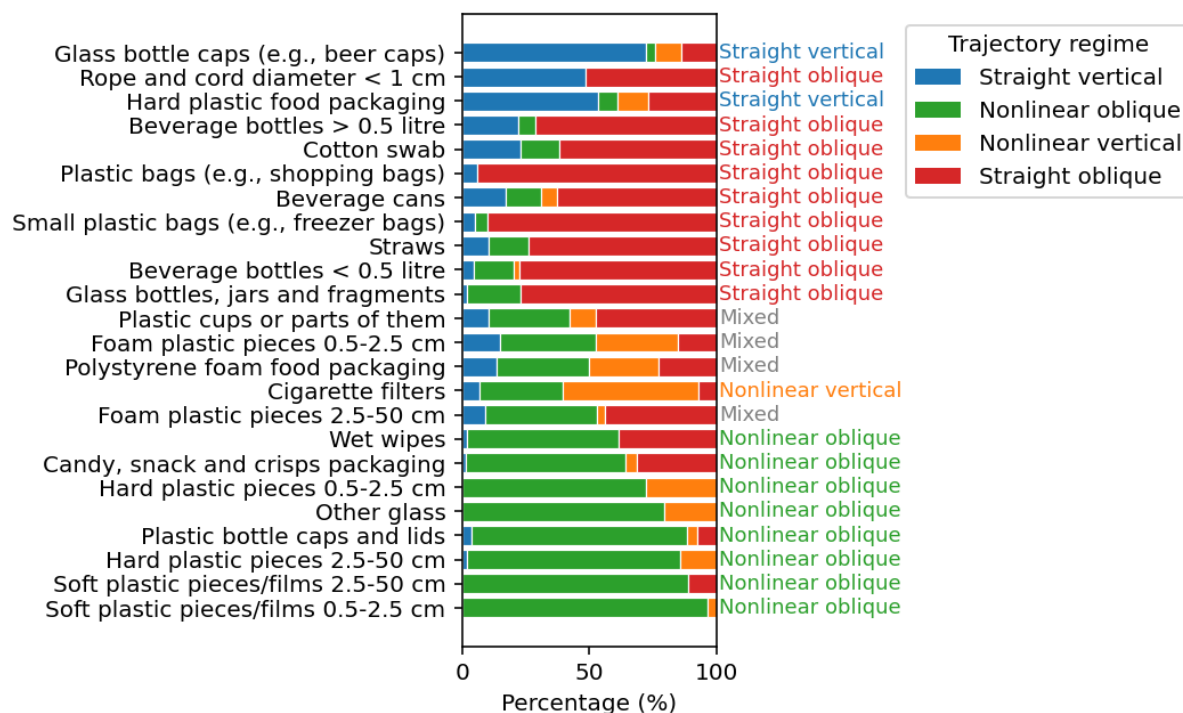
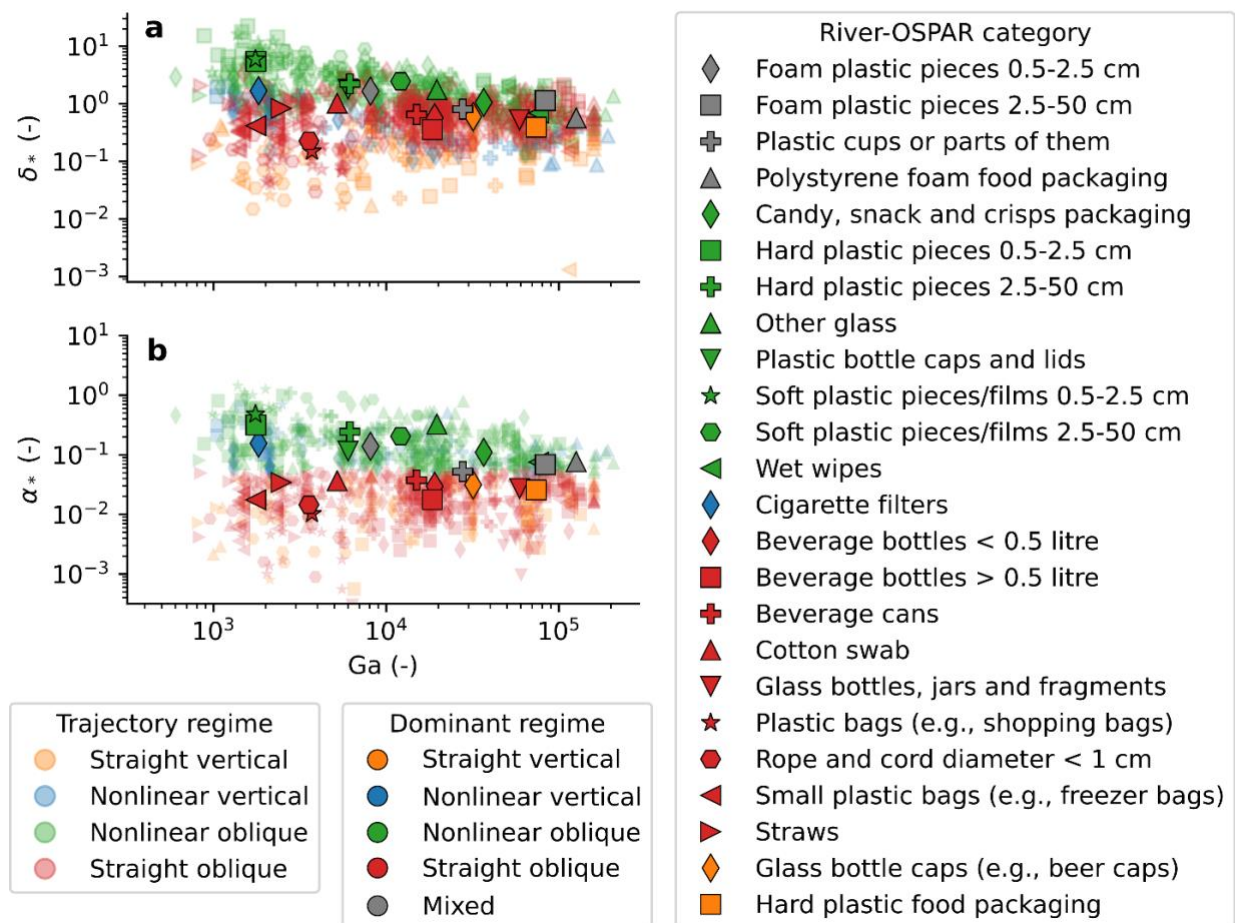


Fig. S2. Percentage splits of observed trajectory regimes (straight vertical, straight oblique, nonlinear vertical, nonlinear oblique) for the 24 River-OSPAR categories tested.

636
637



638
639
640
641
642
643
644

Fig. S3. Scatter plots of litter a) normalised drift (δ_*) and b) amplitude (α_*) as a function of the Galileo number (Ga). Faint markers denote individual litter trajectories, coloured by their classified trajectory regime (straight vertical, straight oblique, nonlinear vertical and nonlinear oblique). Bold markers represent River-OSPAR category mean value, coloured by their dominant regime (over 50% of trajectories belonging to a single regime).

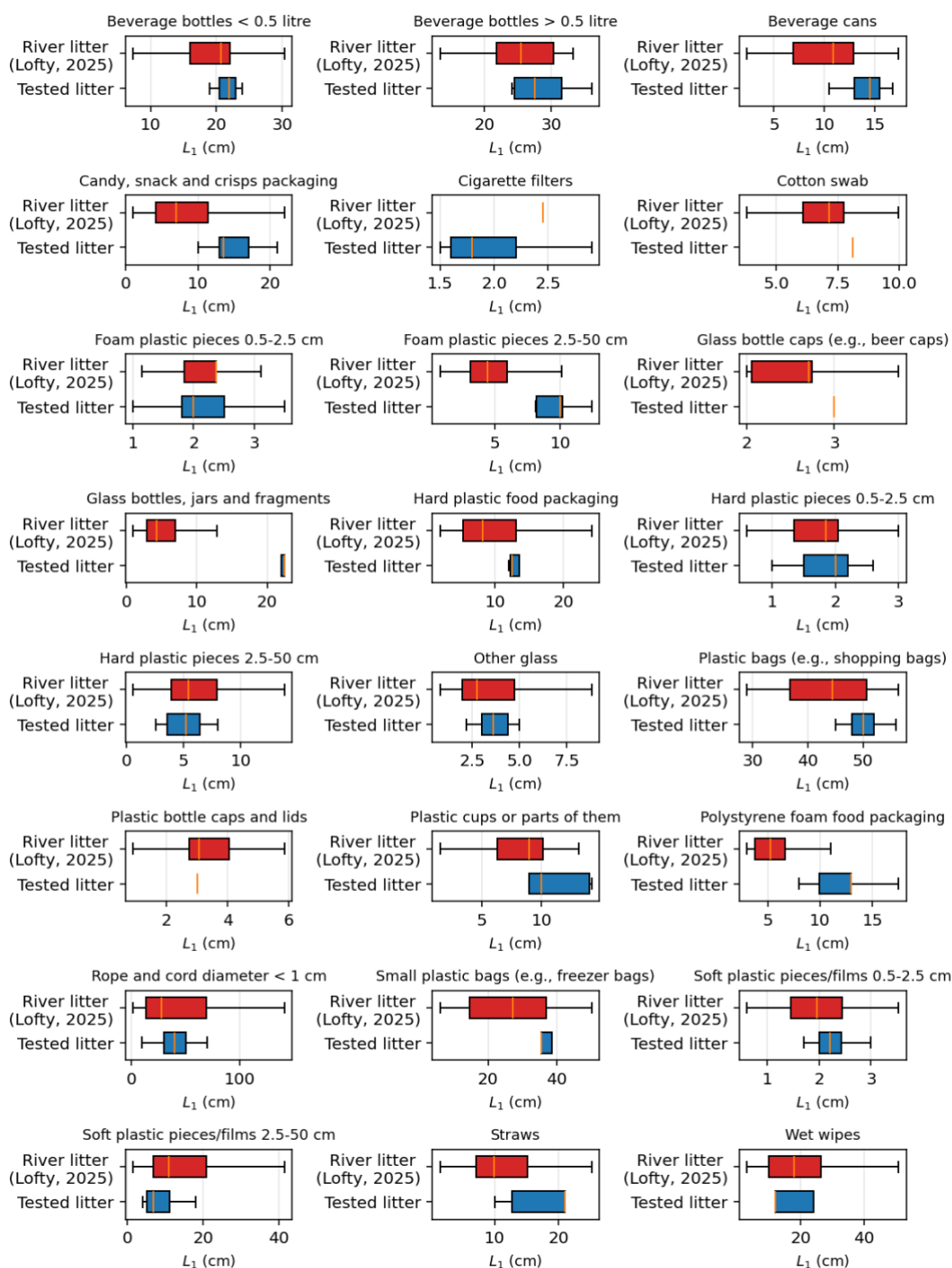


Fig. S4. Verification of the representativeness of the litter tested in this study against litter found in river environments. Boxplots of river litter longest dimension (L_1) comparing the synthetic dataset of river and riverbank plastics generated by Lofty et al. (2026), based on river plastic measurements reported by de Lange et al. (2023), with the litter samples tested in this study across the 24 River-OSPAR categories.

653 **Supplementary Tables**

654 Table S1. Calculated drag coefficients (C_d) for river litter and their interquartile (IQR) range

River-OSPAR Category	Median C_d	IQR25	IQR75
Beverage bottles < 0.5 litre	1.59	1.28	2.00
Beverage bottles > 0.5 litre	1.22	0.88	1.78
Beverage cans	1.12	0.91	1.39
Candy, snack and crisps packaging	0.53	0.21	0.93
Cigarette filters	5.92	1.88	7.23
Cotton swab	1.13	0.80	1.31
Foam plastic pieces 0.5-2.5 cm	3.00	2.21	6.62
Foam plastic pieces 2.5-50 cm	1.00	0.83	1.19
Glass bottle caps (e.g., beer caps)	1.05	1.02	1.10
Glass bottles, jars and fragments	3.06	2.06	4.05
Hard plastic food packaging	1.06	0.93	1.34
Hard plastic pieces 0.5-2.5 cm	0.87	0.6	1.31
Hard plastic pieces 2.5-50 cm	0.90	0.49	1.29
Other glass	1.54	1.34	1.76
Plastic bags (e.g., shopping bags)	0.09	0.04	0.15
Plastic bottle caps and lids	2.15	1.83	2.41
Plastic cups or parts of them	0.76	0.59	0.92
Polystyrene foam food packaging	1.33	1.05	1.72
Rope and cord diameter < 1 cm	0.66	0.24	1.14
Small plastic bags (e.g., freezer bags)	0.02	0.01	0.06
Soft plastic pieces/films 0.5-2.5 cm	0.20	0.11	0.34
Soft plastic pieces/films 2.5-50 cm	0.17	0.06	0.33
Straws	0.26	0.17	0.40
Wet wipes	4.51	2.81	6.43

655

656

662 **Data S1. (separate file)**
663 Complete dataset and litter detection and reconstruction codes available at
664 <https://zenodo.org/records/23245210>
665
666
667
668
669
670
671
672
673
674
675
676
677
678
679
680
681
682
683
684
685
686
687
688
689
690
691
692
693
694
695
696
697
698
699
700
701