



Research Paper

River-to-sea plastic pollution: A pilot toolbox for the Caspian Sea

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HIGHLIGHTS

- Scalable framework for plastic assessment in semi-enclosed coastal environments.
- UAV surveys and modeling enable cleanup validation and seasonal debris tracking.
- Community-led efforts expanded institutional support and monitoring networks.

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ABSTRACT

This study presents the first integrated assessment of plastic pollution at the Kura River delta, where the river enters the hydrologically enclosed Caspian Sea. We applied a modular toolbox comprising four complementary components: high-resolution hydrodynamic modeling to predict debris convergence zones, UAV-based mapping to survey shoreline conditions, automated object-based image analysis for debris detection and classification, and standardized field monitoring by trained community participants for ground-truthing and source identification. Using this framework, we identified debris accumulation hotspots and developed a replicable approach for assessing plastic pollution in semi-enclosed systems. Surveys along a 1.2 km shoreline recorded over 600 items, dominated by beverage containers by count and marine-sourced plastics by weight. Transboundary inputs were confirmed through labeled debris from five countries. The initiative also expanded institutional collaboration, trained over 150 participants, and established a local monitoring network. These findings highlight the value of integrating technical diagnostics with community engagement to enable scalable, site-adapted responses to plastic pollution.

1. Introduction

Plastic pollution remains a pervasive global threat, with over 8.3 billion metric tons produced since the 1950s and only 9% recycled (Geyer et al., 2017). Each year, up to 12 million metric tons of plastic enter aquatic environments, posing risks to biodiversity, ecosystem services, and food security (Jambeck et al., 2015; Gall and Thompson, 2015; Law, 2017). While land-based sources transported by rivers dominate marine plastic inputs (Lebreton et al., 2017), research has largely focused on open ocean systems, leaving semi-enclosed water bodies underexplored (Kosarev, 2005; Ghayebzadeh et al., 2020; Ginzburg et al., 2021; Manbohi et al., 2021).

The Caspian Sea, the world's largest enclosed inland basin, lacks natural outflow and exhibits limited internal circulation, functioning

as a terminal sink for plastics and other contaminants (Kosarev, 2005; Ginzburg et al., 2021). Recent studies report widespread microplastic presence in Caspian waters, sediments, and biota (Ghayebzadeh et al., 2020; Manbohi et al., 2021). Key pollution sources include mismanaged waste, fishing, tourism, riverine inflow, and direct discharge (Gholizadeh et al., 2024; Azadkar Langroudi et al., 2024).

Among the major inflows, the Kura-Aras basin, shared by Turkey, Georgia, and Azerbaijan, is a critical yet poorly monitored contributor. The Kura River delivers substantial plastic loads to the southern Caspian, but lacks standardized assessment protocols (Mousavi et al., 2025). Modeling and field observations suggest long-term retention of debris at the Kura delta due to low-energy hydrodynamics and sediment-trapping features (Lahijani et al., 2024; Van Emmerik et al.,

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Fig. 1. Transboundary map of the Kura-Aras River Basin. The Kura River discharges into the Caspian Sea near Neftchala, Azerbaijan. Source: Adapted from EUWI+ (Plus, 2024).

2022; Ginzburg et al., 2024). With over 90% of regional waste mismanaged, plastic inputs are expected to increase without intervention (Kaza et al., 2018).

The Neftchala coastline, adjacent to the ecologically significant Qizilagach Bay and Ramsar site, represents a high-risk convergence zone for debris accumulation. Its shallow estuary, limited flushing, and mudflat geomorphology make it a natural trap for plastic waste (Ginzburg et al., 2024; Li et al., 2016).

Despite mounting evidence of contamination, effective response is constrained by the absence of regionally adapted monitoring frameworks. This pilot study addresses that gap by applying an integrated methodological toolbox at the river-to-sea interface of the Kura River. It comprises four complementary components – high-resolution hydrodynamic modeling, UAV-based shoreline mapping, automated object-based image analysis, and standardized field monitoring by trained community participants – applied to assess shoreline and floating debris accumulation over a 1.2 km transect at the Kura River delta during two seasonal campaigns (August 2021 and November 2022). The goal is to demonstrate a transferable and scalable model for diagnosing and managing plastic pollution in enclosed and semi-enclosed coastal systems.

2. Integrated methodological toolbox

This study developed a modular toolbox to assess plastic accumulation at the river–sea interface of the hydrologically enclosed Caspian Sea. The approach integrates hydrodynamic modeling, UAV-based shoreline mapping, automated object-based image analysis, standardized field monitoring, and stakeholder engagement in an iterative assessment framework (Fig. 2) (Van Emmerik et al., 2022; Merlino et al., 2023; Jambeck and Johnsen, 2015). The study area is located near Neftchala on the southwestern Caspian coast, where the Kura River delta forms a low-energy estuarine environment (Fig. 1). The exact 1.2 km pilot transect used for field surveys is marked on the map for clarity.

Hydrodynamic simulations were conducted using the Finite Volume Coastal Ocean Model (FVCOM) (Chen et al., 2003) over the full southern Caspian basin, with horizontal grid resolution refined to ~10 m near the Kura River mouth. The model was forced with 2020 ECMWF wind fields and river discharge data from the Girag Kasaman hydrological station, run for the full year 2020 to capture seasonal hydrodynamic variability, and used to identify persistent low-energy convergence zones aligned with observed plastic accumulation (Ghaffari et al., 2013, 2025).

Model outputs guided the selection of the pilot transect, chosen for its modeled retention potential, proximity to the Kura inflow, and confirmed accessibility for UAV flights and shoreline surveys (Meijer et al., 2021; Ghaffari et al., 2025). Two field campaigns (August 2021, November 2022) were conducted to support temporal comparability following a Reproducible Assessment Pipeline (RAP) (National Academies of Sciences, Engineering, and Medicine, 2019).

Prior to each campaign, over 2000 high-resolution UAV images were acquired at altitudes of 30–100 m during low tide and processed into georeferenced orthomosaics (UTM-WGS84 Zone 39S). Image analysis in Trimble eCognition Developer (Trimble Inc., 2024) applied object-based segmentation and supervised classification trained on annotated, field-verified plastic samples (Gonçalves et al., 2020; Martin et al., 2018; Merlino et al., 2020). This workflow enabled the detection of colored plastics and derelict fishing gear, although spectral confusion with light-colored substrates limited white plastic classification.

Shoreline surveys targeted the same 1.2 km transect and followed standardized protocols adapted from the Ocean Conservancy and Deep Dive methods (Falk-Andersson, 2021; De Frond et al., 2025). Field teams – comprising trained community participants and project scientists – collected, photographed, and geotagged each debris item, classifying it by type, source category, and behavioral origin. All recovered waste was bagged, logged, and transferred to certified recycling facilities in Baku.

Institutional partners contributed across project phases: national research institutes and NGOs co-led survey design, field implementation, and data analysis; governmental agencies facilitated site access, provided logistical support, and coordinated waste transfer; and private sector partners contributed transport, equipment, and dissemination of results through outreach activities and stakeholder workshops.

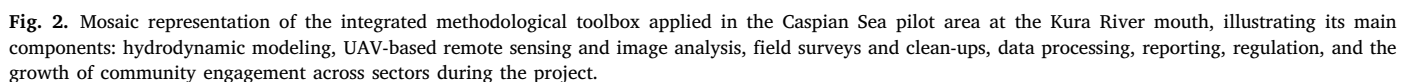
By integrating basin-scale hydrodynamic modeling with high-resolution UAV mapping, automated image classification, and ground-validated field data, the toolbox enables robust identification of accumulation drivers, supports adaptive monitoring, and is transferable to other semi-enclosed systems where conventional diagnostics are limited (Ghaffari et al., 2025; Van Emmerik et al., 2022).

3. Composition and accumulation

Temporal comparison of the two field campaigns revealed both stable patterns and notable shifts in plastic composition along the 1.2 km shoreline transect. A statistical summary of item counts, proportions, and temporal changes between surveys is provided in Fig. 3 and the accompanying tables, summarizing category-level composition and country-of-origin profiles. Non-alcoholic PET bottles and associated components (caps, rings, labels) consistently dominated the debris profile, accounting for approximately 82% of total items across both surveys combined. Their widespread presence – despite interim cleanup – indicates rapid reaccumulation, high mobility, and dual sourcing from riverine transport and local littering (Lebreton et al., 2017; van Emmerik and Schwarz, 2020; Jambeck and Johnsen, 2015). Their floatability aligns with model-predicted convergence near the Kura River mouth (Ghaffari et al., 2013).

Other categories remained stable. Household cleaner containers appeared exactly 12 times in both surveys, suggesting localized, low-mobility inputs likely from chronic domestic leakage or runoff rather than episodic activity (Browne et al., 2011; Ryan et al., 2009; Haarr et al., 2022). This pattern indicates entrenched waste pathways with limited seasonal variation.

In contrast, fishing-related debris declined from 23 to 14 items. Comprising nets, ropes, and lines, these bulky items are typically more visible and more effectively removed. Their decline may reflect successful cleanup and limited re-entry, possibly due to reduced gear loss or changing fishing intensity (Macfadyen et al., 2009; Richardson et al., 2019).



Together, these results reflect a complex pollution landscape shaped by land-based inputs, marine activity, and hydrodynamic retention. The repeated detection of mobile items, partial retention of heavier gear, and an increase in tourist-associated waste underscore the value of reproducible surveys. Transboundary labeling evidence further highlights the need for regional coordination and harmonized monitoring (Gacutan et al., 2022; Maximenko et al., 2019). Consistent with recent multi-diagnostic frameworks (Ghaffari et al., 2025), this study illustrates the potential of integrated, field-validated tools for understanding plastic accumulation at critical coastal interfaces.

The initiative began with 5 core institutions from academic, civil, and governmental sectors, and grew to involve 18 entities by the second campaign, a 260% increase. This expansion was facilitated through clean-up campaigns, workshops, and shared data events, supporting evidence that diverse engagement enhances both scientific quality and societal relevance (Payne-Sturges et al., 2015; Schmitz et al., 2010). A qualitative breakdown of sectoral participation is shown in Table 1 and Fig. 2.

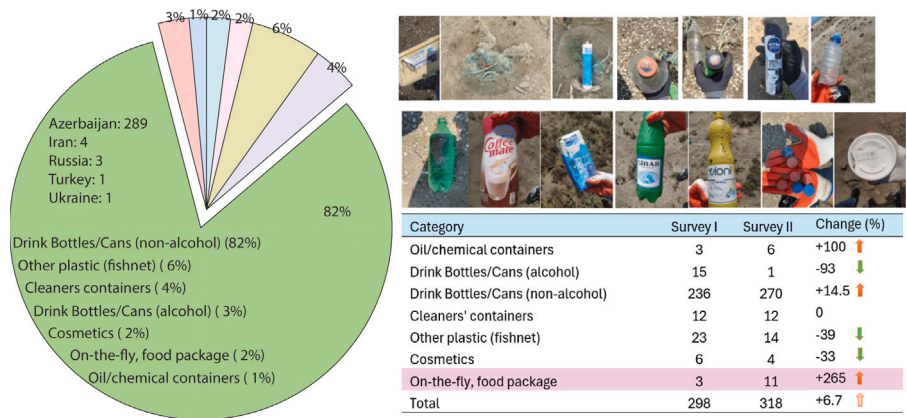


Fig. 3. Summary of plastic debris composition and trends from field surveys at the Kura River mouth. The pie chart shows item distribution, with non-alcoholic drink containers dominating (82%). Tables indicate item origin and temporal variation across the two surveys. Top images display representative plastic debris types, including branded transboundary waste.

Table 1
Growth in institutional engagement across sectors (Qualitative overview).

Sector	Initial partners	Final partners	Growth level
NGOs	2	2	Steady
Academic	2	2	Steady
Public Institutions	1	3	Moderate
State Authorities	0	1	Moderate
Private Sector	0	10	High
Total	5	18	Significant

Private sector involvement, initially absent, expanded markedly to ten partners, contributing logistics, co-hosting outreach, and supporting dissemination. This uptake indicates an evolving civic awareness and a shift toward broader environmental accountability, consistent with trends in sustainability partnerships (Jones, 2023).

Workshops held in Neftchala and Baku drew over 150 participants, offering training on debris classification, shoreline surveying, and geotagging. All materials were shared in Azerbaijani via open-access channels, reinforcing inclusivity and capacity-building. These sessions seeded the *Neftchala Plastics Group*, a community working group that continues post-project as a local anchor for monitoring and dialogue.

International partners contributed technical training and visualization support, aligning local work with regional marine litter protocols and reinforcing scientific standards through co-developed outputs (Robinson et al., 2024).

Overall, the participatory model strengthened institutional memory, expanded local capacities, and reinforced public commitment to reducing marine litter. The integration of stakeholders – especially new private partners – underscores the potential of inclusive, hybrid science-society models to support actionable and scalable solutions for plastic pollution, particularly in semi-enclosed coastal systems (Robinson et al., 2024; Payne-Sturges et al., 2015; Schmitz et al., 2010).

5. Local practice in global context

This study provides insights into plastic pollution dynamics in semi-enclosed and understudied systems, using the Caspian Sea as a case study. In contrast to tropical river systems that rapidly export plastic from dense populations to open oceans (Jambeck et al., 2015; Lebreton et al., 2017; Van Emmerik et al., 2022), the Caspian is shaped by hydrological entrapment, slow circulation, and long retention times.

A key finding is the decoupling between item count and mass: while PET bottles and wrappers dominate by number, derelict fishing nets, though less frequent, contribute most of the mass. This aligns with

observations in northern European waters (Kershaw, 2016; Macfadyen et al., 2009), underscoring how count-based surveys may underestimate the impact of heavy, persistent materials.

The Kura River basin exemplifies a retention-dominated system. With its long course, series of dams, and broad floodplain, much plastic is likely trapped upstream, echoing global findings that only a small fraction of mismanaged plastic reaches the sea (Meijer et al., 2021). Once in the Caspian, limited circulation further reduces export, reinforcing the system’s role as a sink rather than a conduit (Van Emmerik et al., 2022).

These findings challenge the generalizability of global assessment tools optimized for marine-outflowing systems. Mitigation technologies such as booms and traps are poorly suited to submerged or heavier items like nets, which dominate here by mass (Macfadyen et al., 2009; Kershaw, 2016). Behavioral sources – including artisanal fishing, illegal dumping, and seasonal tourism – also imprint regional characteristics on debris profiles.

Accordingly, this study supports a shift from universal export models to place-specific diagnostics that reflect local hydrodynamics and source types. The Caspian’s plastic sink behavior highlights the need for adaptive, regionally informed strategies. As the United Nations Environment Programme stresses, plastic mitigation must “recognize site-specific variation in plastic sources and behavior” (Kershaw, 2016; UNEP, 2021). By integrating modeling, classification, and participatory observation, this work offers a replicable framework for non-marine outflowing systems where tailored approaches can replace “one-size-fits-all” solutions.

The modular design of the toolbox enables adaptation to diverse coastal and riverine contexts by adjusting spatial resolution, survey frequency, and stakeholder engagement strategies according to local environmental and institutional conditions. However, this pilot application faced several limitations, including restricted seasonal coverage due to pandemic-related restrictions, which affected volunteer mobilization and coordination, reduced accuracy in detecting white plastics in aerial imagery, and logistical constraints on UAV deployment during adverse weather. Future developments could incorporate higher-frequency monitoring, integration of satellite and UAV data streams, and automation of debris classification workflows. Additional components could also be integrated where appropriate—for example, drifter-based observations combined with high-resolution transport modeling (Ghaffari et al., 2025), which have provided detailed insights into plastic item dynamics and deposition in a tidal channel and could be valuable in riverine systems. Embedding the approach within national and regional monitoring frameworks would further enhance policy relevance and support coordinated responses to transboundary plastic pollution.

6. Conclusions

This pilot study demonstrates that science-based, locally adapted approaches can improve the understanding and mitigation of plastic pollution at river-to-sea interfaces, even in environmentally complex and geopolitically sensitive settings such as the Caspian Sea. By applying an integrated methodological toolbox – combining hydrodynamic modeling, UAV-based sensing, automated image analysis, field surveys, and participatory engagement – the study mapped plastic accumulation hotspots, characterized debris composition, and traced source dynamics in a semi-enclosed marine system.

Within a narrow 1.2 km coastal transect, plastic debris from five different countries was identified, highlighting the transboundary nature of plastic pollution in the Caspian region and the need for coordinated regional responses.

The modular design of the toolbox offers clear potential for application in other coastal and riverine systems, with components that can be adapted, expanded, or refined according to local conditions and emerging technologies. This flexibility provides a strong foundation for advancing integrated monitoring and management of plastic pollution in diverse environmental and governance contexts.

The initiative also expanded stakeholder engagement from five to eighteen institutions across public, private, and civil society sectors, supporting a shift toward shared responsibility and sustained local monitoring capacity.

Overall, the results show that pairing advanced technical methods with local insight and inclusive governance can deliver practical, scalable solutions. The framework developed here is transferable to other enclosed or data-poor aquatic systems, where conventional diagnostics may be limited, and offers a model for aligning scientific assessment with community-based implementation.

CRediT authorship contribution statement

Peygham Ghaffari: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Bert van Bavel:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alexei Bambulyak:** Writing – review & editing, Methodology, Data curation. **Nils Erik Johansen:** Writing – review & editing, Software, Formal analysis, Data curation. **Elnur Safarov:** Writing – review & editing, Resources, Methodology, Investigation.

Declaration of competing interest

The authors 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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Data availability

Data will be made available on request.

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