Mitigating Riverine Microplastic Flux into Coastal Wetlands via Engineered Bioretention Cells: A Field-Validated Retention Efficiency Model for Subtropical Estuarine Systems

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Abstract. Microplastic transport through riverine corridors into coastal wetland ecosystems represents a critical and insufficiently quantified pathway of anthropogenic polymer contamination. This study presents a field-validated retention efficiency model developed for subtropical estuarine systems, integrating bioretention cell infrastructure with real-time particle-size fractionation monitoring across three instrumented catchments in southeastern Brazil. Sampling campaigns conducted over 24 months captured seasonal hydrological variability, enabling robust parameterization of a modified SWAT+ framework augmented with microplastic fate-and-transport subroutines. Engineered bioretention cells demonstrated mean retention efficiencies of 78.4% for fibrous polymers (≤500 µm) and 64.1% for pelletized resin fragments under peak discharge conditions. Substrate depth, hydraulic residence time, and vegetation density emerged as the dominant design variables governing removal performance. The proposed model offers a scalable, cost-effective engineering design framework applicable to deltaic and estuarine management programs globally.

Keywords: microplastic riverine transport, bioretention cell efficiency, coastal wetland contamination, estuarine polymer fate-and-transport, SWAT+ microplastic parameterization, subtropical hydrological modelling, anthropogenic particle retention, engineered green infrastructure, wetland stormwater management

Introduction

The proliferation of synthetic polymers in freshwater and coastal ecosystems has emerged as one of the defining environmental crises of the 21st century. Microplastics — broadly defined as discrete polymer particles or fibres with a longest dimension of less than 5 millimetres — now pervade virtually every aquatic compartment on Earth, from high-altitude glacial meltwater streams to deep-sea sediment columns. Within this contamination matrix, riverine corridors function as primary conveyance vectors, mobilising terrestrially derived microplastic loads generated by municipal wastewater effluent, stormwater runoff, agricultural mulch film degradation, and diffuse littering into vulnerable coastal receiving environments. Subtropical estuarine wetlands are particularly susceptible to accumulative microplastic loading due to their inherently low hydrodynamic flushing rates, high organic sediment trapping capacity, and ecological sensitivity, harbouring nursery habitats for commercially and ecologically critical species including penaeid shrimp, mugilid mullet, and diverse mangrove-associated invertebrate assemblages. Despite a growing body of literature documenting microplastic occurrence concentrations in estuarine sediments and biota, a critical methodological gap persists: the absence of physically grounded, field-validated predictive models capable of quantifying riverine microplastic flux attenuation as a function of engineered green infrastructure design parameters. Existing fate-and-transport frameworks, including adaptations of the widely applied Soil and Water Assessment Tool (SWAT), have largely omitted explicit microplastic subroutines, relying instead on proxy suspended-sediment algorithms that inadequately represent the density-independent buoyancy behaviour and surface-charge-mediated aggregation dynamics characteristic of synthetic polymer particles. This modelling deficit directly constrains the ability of coastal catchment managers, municipal engineers, and environmental regulators to design and size bioretention infrastructure with defensible performance guarantees under variable hydrological forcing. The present study addresses this gap through a tripartite methodological approach. First, a 24-month multi-season field monitoring programme was executed across three instrumented subtropical river catchments in the state of Santa Catarina, Brazil, generating a high-resolution dataset of microplastic particle-size distribution, polymer-type composition (confirmed via μ-FTIR spectroscopy), and reach-scale mass flux. Second, the acquired empirical dataset was used to calibrate and validate a modified SWAT+ modelling framework incorporating newly developed microplastic fate-and-transport subroutines that explicitly account for particle buoyancy class, hydraulic residence time, biofilm-mediated heteroaggregation, and vegetation-induced flow retardation within bioretention cells. Third, a sensitivity and uncertainty analysis was performed to isolate the dominant design variables — substrate depth, plant species composition, and inlet hydraulic loading rate — governing retention efficiency across a range of synthetic storm events. The paper is structured as follows: Section 2 describes the study catchments, field instrumentation, and laboratory analytical protocols; Section 3 details the SWAT+ microplastic module architecture and calibration procedure; Section 4 presents model performance metrics and scenario-based retention efficiency results; Section 5 discusses design implications for subtropical estuarine catchment management; and Section 6 synthesises key conclusions alongside recommendations for model transferability to other climatic and geomorphic settings.

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