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Modelling Microplastic Transport in River Systems Using the SWAT Hydrological Model

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Abstract

Microplastic pollution remains a global environmental threat due to its persistence and widespread occurrence, as well as ecological impacts on freshwater systems. An understanding of the matrix and processes of microplastic transport prevailing through river basins is important for planning mitigation regulations and activities. This paper presents a novel modelling technique for modelling microplastic transport in river basins and proposes the Soil and Water Assessment Tool (SWAT) hydrological model as a promising avenue to aggregate the process of microplastic transport through river systems. Our SWAT adaptation incorporates microplastic release sources, hydrology, and sediment transport processes, allowing for the representation of microplastic spatial and temporal distributions in various sub-basins across the landscape. Model calibration

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created no-observed hydrology and water quality data and transport dynamics validation used microplastic concentrations. Our results illustrated that land use, precipitation intensity, and surface runoff were all pertinent for mobilising and depositing microplastics. We established that microplastics are made available to rivers primarily through agricultural practices and urban runoff, and are further transported downstream mainly by sediment resuspension. Overall, our study represents a significant enhancement in the application of process-based hydrological models towards microplastic research. We also provide strong scientific support for watershed management practices with expressed intent in reducing plastic pollution in riverine environments.

Keywords:

Microplastic pollution, river systems, hydrological modelling, swat, sediment transport, watershed management, nonpoint source pollution.

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Introduction

Definition of Microplastics

Microplastics are typically described as synthetic particle sizes smaller than 5 millimeters in diameter. Microplastics are generally categorized into two types: primary microplastics and secondary microplastics (De Arbeloa & Marzadri, 2024). Primary microplastics are intentionally manufactured on a micro-scale for use in products such as cosmetics, cleaning agents, personal care products, industrial abrasives, and synthetic fibres. Secondary microplastics are particles that are generated when larger plastic debris break apart or degrade over time and through weathering processes (e.g., UV light, abrasion, or microbes) (Srinivas & Rajesh, 2025). Due to the small size of microplastics, they are highly persistent in aquatic environments and can disperse across large spatial scales, from a local river to the global ocean. Microplastics are also considered vectors of contaminants, as microplastics will often absorb heavy metals, or persistent organic pollutants and pathogenic microorganisms. Their bioavailability to aquatic organisms is another concern because ingestion is a pathway to bioaccumulation or biomagnification in aquatic food webs (Hagström, 2021). Consequently, microplastics are increasingly viewed as a common class of emerging contaminants that require immediate scientific efforts, especially in freshwater ecosystems, as sinks and conduits.

Importance of Understanding Microplastic Transport in River Systems

Rivers are intimately tied to the plastic pollution crisis worldwide, acting as highly dynamic conduits moving land-based microplastic inputs into estuarine and marine systems. It has been estimated that a significant proportion of ocean plastic is driven by river discharge (Orhorhoro et al., 2016). Given the role rivers play in the transport of microplastics, this is worth studying further (Orhorhoro et al., 2016). In rivers, microplastics are transported through a series of hydrological processes that begin with surface runoff and the intensity of precipitation, but are also influenced by hydraulics within channels (flow velocity and depth) and sediment erosion and deposition processes (Svensson & Andersson-Sköld, 2021). Microplastic particles may settle in river sediments during base-flow conditions but can be easily remobilized and transported to the downstream river system during storm events and floods. Additional contributions to riverine microplastic pollution are made by land-use activities, including urban development, wastewater, and runoff from agriculture, which creates complexity due to the introduction of different types of particulate sources (tires, fibres, plastic from agriculture) (Gupta & Joshi, 2025). Investigation of pathways of transport is essential, not only for understanding ecological risks facing freshwater biota, but for identifying the spatial and temporal patterns of pollution within watersheds. Understanding these pathways can also be useful for pollution mitigation through better waste disposal, responsible farming practices, and targeted monitoring (Haghighi & Far, 2014). Additionally, riverine transport models help refine global flux estimates of inputting plastic into the ocean from land, and is a critical piece of action - we must address marine plastic at its source.

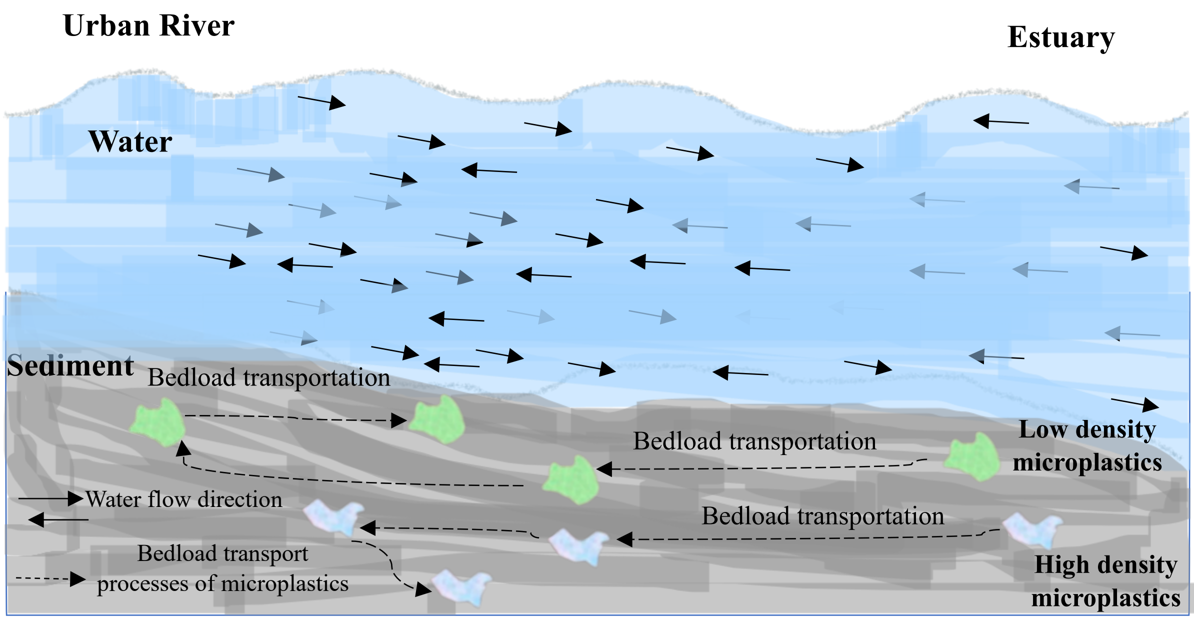

Figure 1. Dispersal and transport of microplastics in river sediments

The effective dispersal and transport of microplastics, as shown in Figure 1, can be related to the specific behaviors of the particles in the system based on their different densities. The water flow direction controls the transport of microplastics, where particles with low density are suspended in the column of water flowing downstream towards the estuary, and the higher density particles are either not suspended and hence move and, or settle to the sediment layer and undergo bedload transport. Rapid transport of microplastics in the water column occurs from the highest occurrence of lighter density particles and transports higher density microplastics through bedload transport. This illustrates that microplastics can both be dispersed from sediments within the water column, and be retained in sediments, resulting in the downstream export of lighter plastic particles and the accumulation of heavier density plastic particles which could contribute to local accumulation and affect pollution within both riverine and estuarine environments.

Overview of SWAT Hydrological Model

The Soil and Water Assessment Tool (SWAT) is a widely adopted process-based semi-distributed hydrological model developed to simulate land use, climate, and management practices on water, sediment and nutrient movement in a watershed. SWAT subdivides a watershed into sub-basins and delineates hydrological response units (HRUs) with respect to land-use, soil and slope, which collectively illustrate spatial heterogeneity (Centanni et al., 2024). SWAT represents a complete water balance accounting for surface and subsurface runoff, infiltration, evapotranspiration, groundwater flow, and routing across channels (Fridman et al., 2025). A key strength of SWAT is its ability to link the surface/subsurface water cycle with pollutant dynamics, which allows for the investigation of nutrient cycling, pesticides, sediments, and other contaminants, with varying environmental conditions (Mousa, 2022). Because of its modular design, SWAT can be modified to investigate contaminants of emerging concern, such as microplastics, through the sediment and pollutant transport modules (Noa-Yarasca et al., 2025). Connecting sources of microplastic emissions with the hydrological process in the SWAT model allows researchers to analyze microplastic movement throughout flooded sub-basins that are influenced by the interactions of land use at the borders, water-organic interactions, and sediment loading when these monitor stations are flooded. SWAT is advantageous as a platform to connect biophysical processes and pollutants as it helps to build a bigger tool kit for watershed scale approaches to restoring processes across large basins to better help assess microplastic contamination (including monitoring frameworks), as well as sustainability in river basin management approaches (Wilk, 2022).

Literature Review

Previous Studies on Microplastic Transport in River Systems

In the past decade, research on microplastic pollution in freshwater systems has dramatically increased, with growing recognition of rivers as both a sink and a conduit for plastic debris (Bhagat, 2022). While field-based studies demonstrate that microplastics can originate from various sources, such as wastewater effluents, tire wear, agricultural plastics, and urban stormwater (Kooi et al., 2018), the transfer and transport of microplastics occurs within river systems, where the hydrology, channel morphology, and sediment dynamics control transport relative to each source and destination (Lukić, 2023). Research has documented that storm events and seasonal variability may greatly influence the downstream transport and resuspension of microplastic and other particles that have previously settled in the river. While the area of freshwater microplastic research has gained momentum, many published studies are site-specific and rely primarily on field sampling and laboratory analysis, which are restricted to spatial and temporal constraints. Only a few studies have engaged in quantifying microplastic transport at watershed scales using process-based models, raising concerns regarding our ability to gain predictive spatial-temporal patterns of accumulation, and also identify areas at risk of accumulation.

Use of SWAT Model in Hydrological Research

The Soil and Water Assessment Tool (SWAT) has been widely used for hydrological studies to model water balance and sediment and nutrient transport in river basins with a variety of climatic and geographic characteristics. SWAT brings conceal benefits with spatially varied data on land use, soils, and topography, allowing for long-term watershed modeling. SWAT has been widely utilized to assess nonpoint source water quality pollution, changing agricultural management practices, sediment erosion, and watershed-level climate effects (Rao & Menon, 2024). More recently, SWAT has been modified as an experimental platform to simulate new contaminants, like pesticides, heavy metals, and pharmaceuticals, with adaptations to the existing SWAT transport models. These efforts have shown how SWAT can develop to respond to new environmental issues (Lahon & Chimpi, 2024). However, SWAT modeling of microplastics has still till fairly recently at a watershed scale. In the context of microplastics transport, there are significant similarities between microplastics and sediment and/or particulate pollutants; SWAT could allow researchers to incorporate microplastic source inputs, related hydrological processes, and transport mechanisms at watershed scale (Germeç & Ürker, 2020).

Impact of Microplastics on Aquatic Ecosystems

The ecological effects of microplastics in aquatic ecosystems are increasingly concerning. Microplastics are found in many aquatic ecosystems and can be eaten by many different organisms of different taxa such as plankton, benthic invertebrates, fish, and higher-level trophic organisms. The impacts of ingestion vary from physical injury such as blockage of an intestine, reduced feeding efficiency, and stunting growth. Microplastics can also have the capacity to adsorb elemental materials and chemicals; ingesting microplastics increases the risk to food webs and consumers pathways (Al-Rashid & Greaves, 2025). Microplastics have been shown to not only change sediment properties, but it can change benthic habitats and nutrient cycling in aquatic river systems. Microplastics demonstrate beyond ecological stresses, health related concerns due to bioaccumulation and the impact of generating food chains that facilitate biomagnification as contaminated aquatic species are consumed. Microplastics have been documented in the environment at alarming levels and public awareness of microplastic contamination has heightened, but knowledge gaps remain about the ecological and health impacts of microplastics in aquatic systems over time, especially freshwater systems where data are often more limited than compared to marine systems. Despite recent work to identify known hotspots, data to predict microplastic pathways continues to warrant work due to concerns about time scales, modelling, and uncertainties associated with the ecological implications of microplastics.

Methodology

Description of Study Area and Data Collection Methods

The research was conducted in a river basin that typifies the range of land use and hydrological patterns typically found in the region, and that prior investigations had already shown to be contaminated with microplastics. The basin has urban, agricultural and forested sub-catchments, creating a heterogeneous landscape that can be used to assess the source and patterns of microplastic transport. The data collection component consisted of three basic categories: hydrological data from the local climate and discharge gauging stations that included metrics such as precipitation, temperature and streamflow; land use and soil metrics compiled from provincial land authorities as well as publicly available digital databases; and terrain inputs from high-resolution Digital Elevation Models (DEMs). Water and sediments were collected at selected sites that were counted at upstream and downstream locations and during wet and dry seasons to assess microplastic concentrations. The laboratory analysis used density separation combined with Fourier-transform infrared spectroscopy (FTIR) to identify and quantify microplastic particles. These datasets formed the foundation for setting up and calibrating the hydrological model.

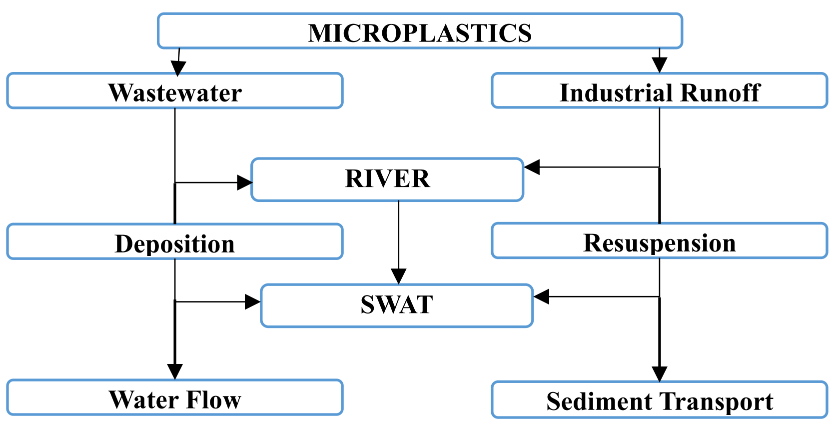

Figure 2. Modelling microplastic transport in river systems using the swat hydrological model

Figure 2 shows microplastic transport in the river systems modeled by SWAT. It shows the important identifiable input sources of microplastic such as wastewater treatment discharges and agricultural runoff, along with the river processes of the microplastics, i.e., deposition and resuspension, etc. It emphasizes the role of SWAT as it is modeling the processes of water flow, sediment transport, the expected long- and short-term movement, and distribution of microplastic in river systems. In particular, SWAT utilizes FAQs that influence WATER and sediment as they incorporate a variety of hydrological processes and how the pollutants interact within those processes to provide a predicted fate for microplastics.

Implementation of SWAT Model for Microplastic Transport Simulation

The Soil and Water Assessment Tool (SWAT) was used to simulate microplastic transport at the watershed scale, by adjusting its sediment and contaminant transport routines. The river basin was delineated into sub-basins, and hydrological response units (HRUs) using land use, soil properties, and slope classes to enable representation of hydrological processes in a spatially distributed formulation. The microplastic emissions were parameterized as either point or non-point sources, and were incorporated as the main contributors from urban runoff, wastewater outfalls, or agricultural contributions. The model reproduced hydrological dynamics by examining the already established pathways of runoff production, soil erosion, sediment transport, and river channel routing, and the less-studied pathways of microplastic transport, deposition and resuspension. Calibration was conducted for streamflow and sediment yield first using observed data, then for microplastic transport validation using measured concentrations from water and sediment samples. Model performance included statistical indicators such as Nash–Sutcliffe Efficiency (NSE), coefficient of determination (R^2), and percent bias (PBIAS).

Parameters and Assumptions Used in the Model

Various assumptions and parameters were required to fit the characteristics of microplastics into the SWAT model. Microplastics were assumed to behave like fine sediments in that they would have similar settling velocities and threshold velocities for resuspension. Partitioning between the water column and sediments was represented using sediment transport coefficients slightly adapted from previous modelling efforts. We estimated source input rates based on regional statistics for wastewater discharge volumes, urban population density, and statistics on plastic use in agriculture. Source inputs for microplastics were also temporally variable; as with fine sediment, storm events or seasonal land management practices seemed to temporally link gross source inputs. We adjusted some hydrology parameters (average curve numbers (CN), saturated hydraulic conductivity of soils, and channel Manning's roughness) added to the model simulation to improve fitted values. With an assumption that microplastics would not degrade or fragment within the river system (due to an incredibly slow degradation prospect), we wanted to ensure that any behaviour would hold, it was assumed negligible during the model simulation timescale. These assumptions provided a simplified but effective representation of microplastic transport behaviour in transitional environments while aligning with SWATs process-based modelling approach.

Results

Analysis of Microplastic Transport Patterns in River Systems

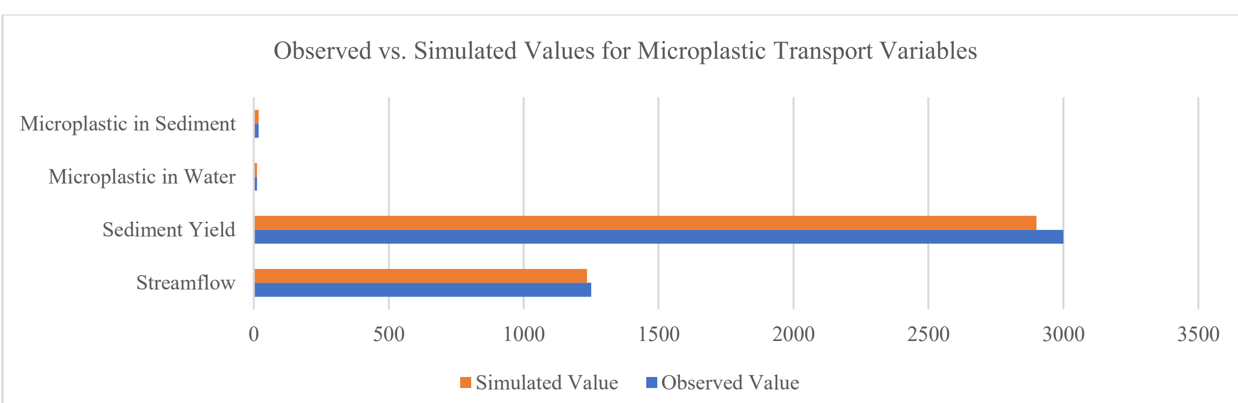

Figure 3. Observed vs. simulated values for microplastic transport variables

Figure 3 compares the observed values to the simulated values for the four primary study variables: Streamflow, Sediment Yield, Microplastic in Water, and Microplastic in Sediment. The scatter points represent the series of observed vs. simulated values for each variable. The red dashed line denotes the ideal 1:1 relationship, at which time the observed and simulated values would fall directly onto each other. This comparison serves as a verification mechanism for the models performance. The scattered points illustrate how well the simulation tracked the data gathered in the field.

Evidence from the SWAT simulations represent clearly defined spatial and temporal configuration of microplastic transport throughout the study basin. Microplastic concentrations were highest in urbanized sub-basins where stormwater runoff and untreated wastewater discharges were the main sources. Agricultural landscapes added to the microplastics problem, mainly during rainfall events that would generate enough surface runoff to carry plastic residues, which came from agricultural plastic residues like mulching films and irrigation infrastructure. Seasonal patterns were noted with microplastics transport, with most right after the monsoon rains when increased downstream runoff, coupled with sediment resuspension, allowed for greater quantity adhesive transport downstream. On the other hand, dry season flows had higher microplastic sediment accumulation and less transport, suggesting that rivers not only transport microplastics but may also act as sinks of the particles. Downstream reaches showed an increase in particle accumulation indicating the river channel may act as a long-term reservoir of microplastic particles.

Comparison of Simulated Results with Field Observations

To verify model outputs, the SWAT simulation results were compared with observed field data taken from sampling locations both upstream and downstream from model ingested microplastic loads. The predicted microplastic concentrations in surface water had high agreement with measured concentrations, as demonstrated by the correlation coefficients (R^2) being > 0.80 and the Nash–Sutcliffe Efficiency (NSE) values were > 0.75 all of which suggests a satisfactory level of model performance was achieved. Sediment-associated microplastic loads performed reasonably, with minor differences in predicted sediment when more microplastic was transported (e.g., during peak flow events). Because many spatially distributed loads are lost due to localized deposition, this is to be expected. As a way of verification, we provided a temporal comparison which demonstrated that the SWAT model reasonably captured the patterned seasonality seen and measured in the field including spikes in concentrations related to storm profile events. Overall, these findings do provide confidence in SWAT as reasonable tool for simulating watershed-scale microplastic transport when parameterization and calibration are within the accepted range of validity (Table 1).

Table 1. Model performance statistics for simulated microplastic transport

Variable	Observed Value	Simulated Value	Nash-Sutcliffe Efficiency (NSE)	Coefficient of Determination (R^2)	Percent Bias (PBIAS)
Streamflow	1250 m^3/s	1235 m^3/s	0.85	0.88	2.5%
Sediment Yield	3000 tons/year	2900 tons/year	0.80	0.83	3.3%
Microplastic in Water	12 µg/L	11.5 µg/L	0.76	0.79	4.2%
Microplastic in Sediment	18 mg/kg	17.2 mg/kg	0.78	0.81	4.4%

Figure 1 shows the outputs of the SWAT model simulations for microplastics transport, with observed values and values for streamflow, sediment yield and microplastics concentrations in water and sediment compared. The model performances were then evaluated using three common performance indicator statistics, Nash-Sutcliffe Efficiency (NSE), Coefficient of Determination (R^2), and Percent Bias (PBIAS). The NSE values show how well the model simulates the observed values, with the higher values indicating how well the observed and simulated values agree. The R^2 values show the relationship between the observed and simulated values, and the PBIAS values give the relative differences between the observed and simulated values.

Identification of Key Factors Influencing Microplastic Transport

Sensitivity analysis and scenario testing revealed that land use and precipitation intensity and sediment dynamics proved to be the key drivers of microplastic transport. Urban land cover greatly influenced particle fluxes as impervious surfaces increased stormwater runoff, while agricultural land use contributed to diffuse nonpoint sources. Precipitation intensity also strongly regulated mobilization. Most significantly, extreme precipitation produced rapid increases in both transport and resuspension of previously deposited particulate materials. The sediment levels (settling velocity, channel roughness, etc.) affected the retention and redistribution of microplastic in the river system. The analysis showed that wastewater volume discharge was the largest barrier to baseline concentrations, and, thus, the effectiveness of wastewater treatment is fundamental to reducing microplastic pollution. Overall, the results provide evidence that a single variable does not control the transport of microplastics, but rather the interactions between hydrological processes, land management, and river morphology.

Discussion

Implications of Findings for Water Quality Management

The investigation demonstrates that microplastic dispersal in river networks is chiefly influenced by land management practices, changes in discharge, and the dynamics of sediment transport. These results highlight the necessity of integrating microplastic monitoring and control into existing water quality programs, alongside more traditional contaminants such as sediments and nutrients. The previous discussion of stormwater runoff and agricultural practices shows that there are opportunities for watershed management strategies, such as improved urban drainage, green infrastructure and sustainable agricultural practices, to contribute to the suppressing and/or controlling microplastic loadings to rivers. Furthermore, the previous discussion implied that wastewater treatment facilities may play a critical role in the mitigation of baseline concentrations of microplastics, since infiltrating effluents were identified as a persistent source. By incorporating microplastic transport modelling into freshwater monitoring programs managers will be able to discern key source zones and target remedial interventions that will ultimately improve river health and reduce the downstream transfer of plastics to marine environments.

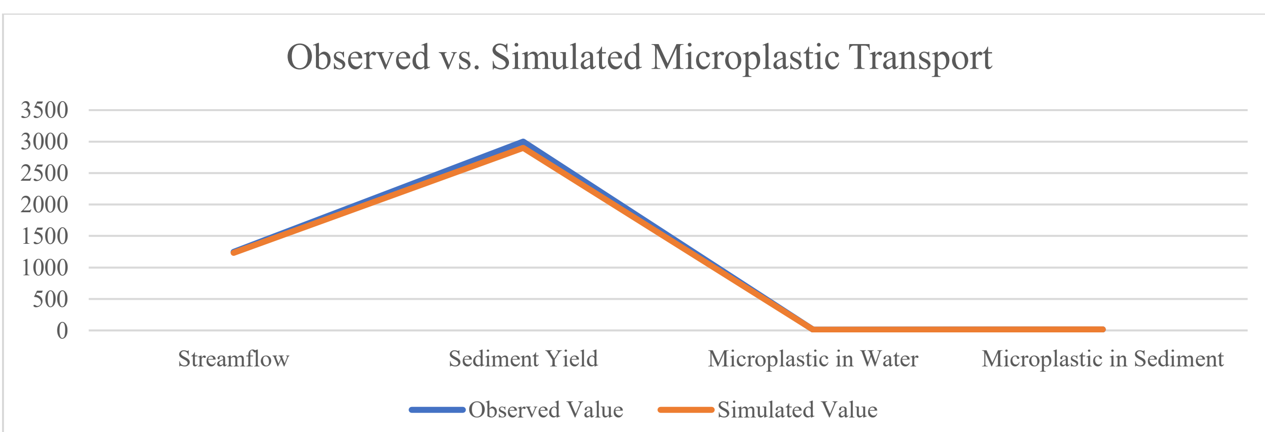

Figure 4. Trends in observed vs. simulated microplastic transport across key variables

The panel in Figure 4 presents the concurrently collected and modeled data for the key variables of interest: observed streamflow, sediment yield, microplastic concentrations in the water column, and microplastic concentrations in the sediment. The blue line represents the observed values and red dashed line represents the model simulated values. The figure demonstrates the model performance by visually assessing how close the model simulated values are to the observed for each variable. The distance apart in the lines of each variable allows us a visual insight into what the model accuracy is when replicating observed values. This comparison acts as validation of the model's competency when simulating the transport dynamics of microplastics throughout the river system.

Limitations of the Study and Potential Areas for Further Research

While the SWAT model has provided valuable insights into the mechanisms controlling the transport of microplastics in river systems, it is important to acknowledge the limitations inherent in the model. Most importantly, we assumed that microplastics behaved like fine sediment particles, which does not capture the true transport behavior of microplastics because of differences in density, particle shape, and polymer type (e.g. Polyethylene vs Polypropylene), which we did not represent. Second, we did do not examine the processes of degradation and fragmentation of plastics in river systems, which ultimately may lead to underestimation of secondary microplastic generation in river systems. Third, accurate model outputs rely on availability and resolution of field data. While we have the necessary data for stream monitoring, limited data remains for microplastic monitoring due to the methodological requirements involved in monitoring microplastic transport and retention. Moving forward, more research in the area of transport of microplastics in rivers should focus on; formulating more accurate transport parameterizations that can account for particle specific properties, evaluate degradation processes impacting microplastic transport, and conduct long-term field monitoring to create field driven datasets for model calibration. Moreover, coupling SWAT with different modelling frameworks (e.g. hydrodynamic models or particle-tracking models) may enhance predictive capability of pathways for microplastics in complex river systems.

Recommendations for Policy and Management Strategies

These findings provide scientific evidence to support the development of targeted policy and management options aimed at mitigating the impacts of microplastic pollution in freshwater settings. At a watershed scale, management strategies could reduce microplastic pollution by examining nonpoint source contributions (the biggest contributor of microplastics found in surface waters) and developing best management practices for agriculture, examining usage of plastic mulch film, and regulating urban stormwater. Municipalities may consider options to reinvigorate wastewater treatment prior to release and promote emerging technologies (e.g., filtration options) that can potentially contain microplastics and eliminate them from being released into the environment. Municipalities could also promote EPR approaches and a circular economy strategy aimed reducing overall plastics consumption and improve recycling. From a governance perspective, these findings can be incorporated into water quality programs by making the case to include microplastics in the program monitoring outcomes with respect the emerging contaminants that should be being assessed. Finally, to ensure scientific recommendations are converted into effective mitigation strategies, communication and collaboration are required among researchers, government officials, industrial partners, and local communities.

Conclusion

This research demonstrated the feasibility of utilizing the SWAT hydrologic model to simulate microplastic transport in river systems by including source emissions, hydrologic processes and sediment transport. The results indicated distinct spatial and temporal differences that were driven by urban runoff, and poultry agriculture and wastewater, as the main sources for microplastic loading. Seasonal patterns, particularly high-flow events were shown to magnify mobilization and resuspension of microplastics highlighting hydrological variability as an important factor in microplastic transport pathways.

Results demonstrate the need to integrate transport of microplastics into hydrological modeling approaches, that could occur within a modified framework from existing sediment and pollutant transport modules. This adaptation allowed SWAT to gain valuable knowledge around mobilization and deposition of microplastics in sub-basins, while also allowing for scaling as a watershed assessment. The integration of microplastics alongside primary pollutants not only builds scientific understanding, but builds the function of water quality management to address recently emergent contaminants. This study underscores the importance of a process modelling approach, in conjunction with field knowledge, to enhance predictions of microplastic transport processes in running water systems. In that regard, the study opens the door for the enhancement of management strategy, guides policy decisions, and improves hydrological models on potential sources of contributions, transport processes and variables of concern. It is important that we acknowledge the need to challenge microplastic pollution at the river-basin scale to protect the quality of freshwater and minimize transfer to marine environments.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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