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Review

Effect of Physical Characteristics and Hydrodynamic Conditions on Transport and Deposition of Microplastics in Riverine Ecosystem

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Abstract: Microplastic disposal into riverine ecosystems is an emergent ecological hazard that mainly originated from land-based sources. This paper presents a comprehensive review on physical processes involved in microplastics transport in riverine ecosystems. Microplastic transport is governed by physical characteristics (e.g., plastic particle density, shape, and size) and hydrodynamics (e.g., laminar and turbulent flow conditions). High-density microplastics are likely to prevail near riverbeds, whereas low-density particles float over river surfaces. Microplastic transport occurs either due to gravity-driven (vertical transport) or settling (horizontal transport) in river ecosystems. Microplastics are subjected to various natural phenomena such as suspension, deposition, detachment, resuspension, and translocation during transport processes. Limited information is available on settling and rising velocities for various polymeric plastic particles. Therefore, this paper highlights how appropriately empirical transport models explain vertical and horizontal distribution of microplastic in riverine ecosystems. Microplastics interact, and thus feedback loops within the environment govern their fate, particularly as these ecosystems are under increasing biodiversity loss and climate change threat. This review provides outlines for fate and transport of microplastics in riverine ecosystems, which will help scientists, policymakers, and stakeholders in better monitoring and mitigating microplastics pollution.

Keywords: microplastics; riverine ecosystem; sedimentation; deposition; settling velocity; plastic density

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1. Introduction

Nowadays, plastics have been widely used because of their low cost, durability, and resourcefulness in socio-economic sectors, like fishing, industry, tourism, and more [1–4]. Plastic pollution gained attention of the scientific community and has been documented across the globe [5]. Plastic particles with a size of less than 5 mm are known as microplastics which have been studied extensively in different ecosystems, such as marine [6–8], wetlands [6,9], rivers [10–12], groundwater [13–15], sub-surface system [14,16,17], atmosphere [18,19], soil [14,20,21], and remote mountain [22–25]. Microplastics are subcategorized as primary and secondary depending upon their origin [26], such as products from cleaning, cosmetic hygiene, paints, detergents, personal care, etc., are considered as primary microplastics; whereas degradation of water from soda bottles, fishing nets, and plastic bags, large-sized plastics into micro-sized are regarded as secondary microplastics [27,28]. Regardless of origin, ample quantities of plastics are inevitably available in natural ecosystems due to the degradation of large plastic particles into smaller micro- or nano-sized plastics [29,30]. Global production aggregates to 6,300 million tons of plastics recently, out of which 79% are disposed into landfill sites and in the aquatic environments [31]. Almost 2.41 million tons of plastics are transported to oceans via rivers annually, projected to increase in the coming decades [32]. Microplastics in freshwater environments have increased attention globally due to their high concentration are being transported and ending up in oceans. For example, 0.33 million tons of plastics had been harvested from the Yangtze River, China [32], and 0.12 million tons of plastics were transported via River Ganga, India, per year [17,33,34]. Hence, substantial knowledge is necessary to understand potential implications of physical, chemical, and biological alteration in microplastic properties and their ecological problems in riverine ecosystems.

To estimate the transport process accurately, it is necessary to understand how plastic particles are carried and deposited in freshwater ecosystems (such as rivers, wetlands, lakes). To date, several field investigations have been conducted across the global freshwater ecosystems [9,11,12,17,35–40], however, limited investigations have been reported so far for exploring the transport of microplastics in different ecosystems [41–46]. Lagrangian numerical simulation model has been used to determine the concentration of microplastics in the marine environment [47–49]. Still, the riverine transport processes have been poorly understood, except for mapping the small particle concentration in the rivers. Though the physical transport of microplastics in the aquatic environs are quite challenging and complicated [50–52], therefore, during the discharge from the river to oceans, microplastics are not only transported but also settled down to the river bed by either accumulation or remobilization mechanism depending upon flow rates [53,54]. Before addressing the transport mechanisms, one question emerges: how plastic degrades into micro- and nano-plastics in the riverine ecosystem. Plastic debris experiences natural interactions, reactions, and translocation; and degrades into macro-, micro-, and nano-plastics in the natural environment through mechanical abrasion, thermal and ultraviolet (UV) degradation, along with photo-degradation, biodegradation, and friction (e.g., mechanical force) [55–58]. Polymeric chemical composition is governed by plastics density which changes over time due to the aging and weathering process or biofilm growth [26,59–61]. As a result, microplastics alterations occur in terms of their physical properties and influence their sinking rate in riverine ecosystems.

In the aquatic ecosystems, the deposition and transport of microplastics in sediments and water profile are determined by hydrologic characteristics, rainfall or storm events, watershed pattern, vegetation, hydraulic conditions, microplastics physical properties (size, shape, and density), and hydrodynamics behavior of microplastics [62–64]. Microplastic particles also possess intrinsic properties depending upon their physical properties, such as size, shape, and density [65,66]. Most of the commercial plastics have densities in the range of 0.85–1.41 g cm^{-3} [5,51,67]. Intrinsic properties of micro-sized particles significantly govern the fate and transport; for instance, polyethylene, polypropylene, polystyrene, and polyurethane with a density less than 1 g cm^{-3} remain suspended in aquatic settings [68]. A high number of low-density polymers remain in suspension due to buoyant force in water columns that get transferred to oceans via rivers. Indeed, plastics of relatively high-density sink directly over the river bed sediments and are subsequently prevalent in the lentic and lotic water systems [11,69–71]. The transport behavior of micro- and nano-sized plastics are significantly governed by natural phenomena, such as buoyancy, gravity, and drag forces [72–74]. Gravity and buoyancy are subjected to be negligible for fine particles (diameter < 2 μm), and the interfacial tension plays a key role in particle movement [75,76]. In addition to this, the relative influence of momentum and force of gravity on plastic particles interpret the deposition and sedimentation mechanisms [77].

Fine particle possesses large surface area and hydrophobicity as compared with coarser particles. Generally, the surface wettability of micro-sized particles also influences the settling velocity and drag coefficient [72]. Thus, the settling mechanisms of microplastics have also been explored in hyporheic zones; therefore, stagnant zones are crucial reservoirs for the long-term microplastics sink, whereas it can be remobilized/resuspended with the higher flow velocity [39,53,54,69,78,79]. In the Inde River, remobilization of microplastics had occurred at the bed substratum for every rise in the flow velocities and water level [54]. Despite the current efforts to address microplastics pollution in riverine ecosystems, the transport behavior of microplastics quantification is poorly understood compared to other nano- or micro-size pollutants present in riverine ecosystems.

Inclusive theoretical models are required for holistic understanding of microplastics pollution due to the transport and sedimentation occurring in the riverine ecosystem. This review will focus, firstly on sources of microplastics, secondly illuminating the effect of environmental conditions on the aggregations of microplastics, third highlighting the governing processes of its fate in the river system, and lastly presenting details on the current development of numerical models of fluid mechanics to analyze the trajectory of microplastics.

2. Sources of Microplastics

Plastics pollution has been acknowledged as the dark side of industrialization for the riverine ecosystems [80,81]. Direct sources of microplastics pollution, such as agricultural runoff [20,82], wastewater treatment plants [83–86], fishing nets/cages [87], municipal wastewater [88–90], washing clothes [84,91–93], and urbanization [17,94–96], have been documented across the riverine ecosystem [39,63,71,97–101]. Resultantly, several studies have reported diverse concentrations of microplastics in the riverine networks due to local and diffuse sources, poor site accessibility, variations in flow regimes, and channel morphology, e.g., depth and size of the river channel [95,102–104]. Increased microplastics concentrations have been observed commonly near an urban area, especially associated with wastewater effluents [86,105,106].

3. Physical Properties of Microplastics Particles

Numerous plastic particles have been deposited in the natural environment; subsequently, the density and texture of microplastics vary substantially, relying on polymeric characteristics and production process. Microplastics are heterogeneous in nature and exhibit distinct behavior, depending on their physical properties, such as particle density, shape, and size [5,55,65,66,107]. Microplastics are found in water columns or floating water due to density differences of the particle and fluid, i.e., buoyancy effect (Figure 1). It has been observed that the density, shape, and diameter of plastic particles can change, either increase or decrease, as a result of fragmentation and degradation of microplastics [44,70,74]. Density, polymeric chemical composition, and shapes of microplastics govern whether microplastics can be buoyant, suspend, or sink in the riverine ecosystems [68,80,108]. High-density microplastics can slide, roll and intermittently bounce at the river bed under low flow velocity, whereas low-density particles can remain in suspended form. As a result, large-sized microplastics particles are more likely to be deposited in the river bed-load sediments [66]. Besides, the influence of water environmental conditions on transport behavior [109], changes in their density, shape, and diameter [26], and surface roughness [110] have not been inspected so far in the riverine environment.

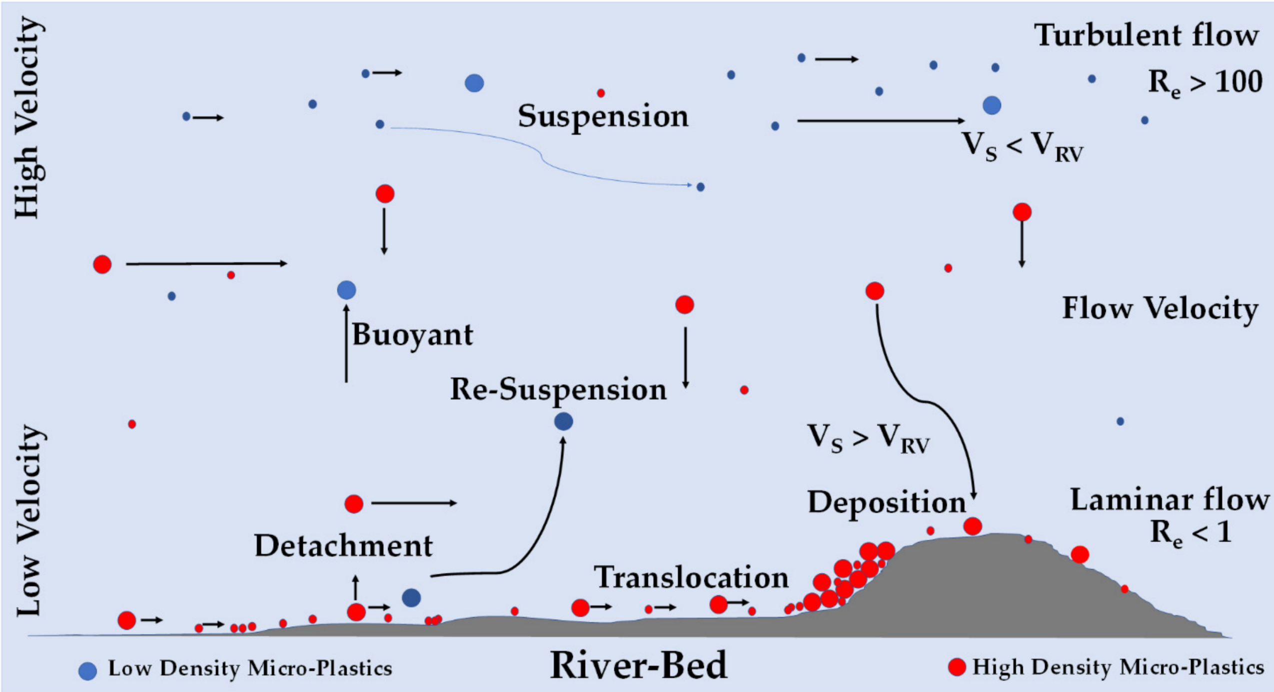

Figure 1. Schematic representation of natural phenomenon occurring for microplastics transport and sedimentation in rivers (V_S denotes settling velocity, V_{RV} is river velocity, and R_e is Reynolds number).

3.1. Specific Density of Microplastics

Particle densities can significantly define the deposition and mobility of microplastics in riverine ecosystems. Commonly, microplastics, in the density range less than the river water, float or remain in suspension, while the higher density microplastics are non-floating particles and tend to deposit over the river bed [69,70,111,112], as shown in Figure 1. Low-density commercial plastics, such as polypropylene (0.85–0.95 g cm^{-3}), polyethylene (0.90–0.99 g cm^{-3}), polystyrene (0.95–1.1 g cm^{-3}) are commonly detected in riverine ecosystems. High-density plastics, including polyvinyl chloride (1.1–1.58 g cm^{-3}), polyamide (1.38–1.45 g cm^{-3}), and polyethylene terephthalate (1.38–1.45 g cm^{-3}) are also present in rivers [5,31,39,113–115]. Plastic virgin materials have a density in the range of 0.01–2.3 g cm^{-3}; however, at the same time, plastic particle density also varies with residence time in the riverine ecosystem due to aggregation, biofilm development, degradation, and flocculation mechanisms [51,60,61,116]. Similarly, in streams, Hoellein et al. [77] observed that the denser fragments can easily be retained and also resist remobilization due to high flow velocities as compared with polypropylene pellets (low-density plastics). Pellets have a slow response time to change their flow velocity in benthic environments [41]. A recent study revealed non-uniform distribution of microplastics along the Hillsborough River depth profile due to the river hydrodynamics [117]. Inherent density of microplastic particles and hydrodynamic turbulent flow condition of river govern the trajectory pathways for low-density plastic particles [26,52,70,117]. Though, the trajectory and speed of microplastics in the riverine ecosystem are complex because of hydrodynamic conditions. River flow dynamics, depending upon the Reynolds number, either laminar ($R_e < 1$) or turbulent ($R_e > 100$) flow can impact the flow dynamics of microplastics with respect to the river depth profile. Figure 1 conceptualized high-density microplastic particles can dominant at the river bottom in laminar flow conditions and low-density microplastics in suspension. However, in the turbulent flow condition, the low-density microplastic particles travel for long-distance but the high-density microplastics can either be in suspension or settle down at the river bottom after certain distance of translocation.

3.2. Shape and Size of the Microplastics

Plastic particles in the riverine ecosystem exist in various shapes, for instance, fibers, pellets, filaments, fragments, films, foams, microbeads, and granules [99,102,115,118–121]. Films and fibers are common irregular shapes obtained from the degradation of garbage, construction work, washing clothes, and greenhouse poly bags and further degraded due to photo-degradation and mechanical abrasion. In general, low-density fibers and films have high buoyancy and low settling velocity [52,122]. Several investigations have documented that fibers can remain in suspension for a longer time as compare to fragments and spherical beads in the riverine sediments [45,70,104,123]. Hoellein et al. [77] also reported that fragments have high deposition velocity, followed by fibers and then pellets; therefore, fibers and pellets possess a longer transport length of particles. For that reason, wide distribution of fiber plastics is found in silt and clay sediments, although medium-sized sand particles enriched with microbeads and pellets are mainly found in riverine ecosystems [104]. Particle shape and surface area are key parameters for the transport of microplastics, as the high surface area to volume ratio state the aggregation and sink behavior of fibers, films, and foams compared to the larger plastic particles [51,52,77,124]. Hoellein et al. [77] observed that uniform shaped plastic particles, such as polypropylene pellets having the lowest surface area to volume ratio, can travel for long-distance, whereas variable shaped plastic, for instance, fragments have the shortest transport length in the streams. As the spherical particles have less exposed surfaces, the shear resistance is less, i.e., less drag force is generally required for initial movement. At the same time, fibers require high shear stress for initiating the movement, as microplastics are strongly trapped in the sediments strongly. Both erosivity or drag force (which is dependent upon the shear stress) and lift force (which is function of the exposed surface) are commonly dependent on the geometry of the microplastics [74]. Under the same conditions, drag force can effectively roll out the uniform spherical-sized particles, and consecutively lift the fibrous particles [74]. Hence, the characteristics of the shape of microplastics influences erosion, for example, spherical and fibrous microplastics, possess different shear stress and lift force in an aquatic setting.

Diameter of plastic particles also affects the transport and sedimentation under different river dynamics. Great contrast in settling velocities of microplastics of varying particle diameters was observed. Thus, the settling and rising velocities of microplastics particles significantly determine the erosivity of microplastics in addition to natural sediments [40,70]. Both settling and sedimentation of microplastics are dominantly influenced by the gravitational force [118]. In the Rhine River, it has been observed that the settling of microplastics is associated with river bed slope, i.e., an increase in flow velocity allows microplastics to travel over long distances [95]. However, Hoellein et al. [77] observed a positive correlation between deposition velocity (V_{dep}) and diameter of microplastics, whereas a negative correlation with the ratio of deposition velocity to settling velocity (V_{fall}) in streams. For V_{dep}/V_{fall} ratio equivalent to 1, deposition of particles occurs under the force of gravity for diameters in the range of ~50 to 500 μm. In contrast, for $V_{dep}/V_{fall} \gg 1$, particles of diameter < 50 μm are retained at high rate, and for $V_{dep}/V_{fall} \ll 1$, particles of diameter > 500 μm experience hydrologic actions, such as momentum and resuspension, both higher than gravitational settlings [77]. As a result, microplastics also experience numerous natural processes during transportation, such as aggregation, degradation, biofouling, flocculation, and ingestion in aquatic environs. Plastic degradation and surface heterogeneity also occur simultaneously, which play a crucial role in the environmental fate of microplastics in aquatic environments [5,107].

4. Influence of Environmental Conditions on Aggregation of Microplastics

Aggregation in rivers, both homo-aggregation and hetero-aggregation, play a key role in microplastics translocation, depending upon the shape, size, and density of microplastics [38,107,125–127]. Wang et al. [107] stated that aggregation is a key physico-chemical process that dominates the horizontal and vertical movement of microplastics in the aquatic setting. Besides, horizontal transport via flow velocity, slope, wind, and turbulent forces led to the buoyancy of the settled microplastics in suspension. In vertical mixing, buoyant microplastics can be transported as slow as suspended soil/sediments via floatation in the aquatic medium. Therefore, Kooi et al. [126] mentioned that the settling velocity of microplastics increases due to aggregation. As stated above, the aggregation is governed by plastic properties (e.g., size, shape, density, and aging), also depends upon the environmental conditions of water, such as pH, surfactant, organic matter contents, metal ions, and other toxic chemicals. Therefore, plastics of large size possess higher stability and less aggregation in the water environment as compared to small particle sizes [128]. Microplastics being hydrophobic in nature shows aggregation behavior due to steric effects (e.g., the force of attraction due to surface charge/steric hindrance). Therein, higher ionic strength ($Fe^{3+} > Na^{+}$) also increases the aggregation process [129–131].

Microplastics retain the electrostatic force of attraction at low pH (<3), which leads to the aggregation of microplastics [129]. At the same time, for natural water conditions (pH > 6.5 and < 9), disaggregation of microplastics results in constant hydrodynamic diameter due to dominating electrostatic force of repulsion. In addition, due to steric hindrance, humic acid has oxygenated functional groups which encourage microplastics to aggregate at low pH (<4), whereas no effect has been observed at relatively higher pH [129]. Similarly, surfactants behave as a stabilizer at high concentrations in aquatic environs; therefore, the stability of microplastics (e.g., polystyrene) colloidal particles get disturbed and tend to aggregate together [132].

In natural aquatic environments, microplastics aggregates with other constituents, such as organisms, clay sediments, metallic oxides, and so on, which ultimately leads to heterogeneous aggregation of microplastics [107]. Microplastics encourage microbial colonization and biofilm development depending upon the microplastics properties, microorganisms species, and water environmental conditions [60,61,133]. Miao et al. [60] observed that biofouled polyethylene terephthalate (PET) and polyvinyl chloride (PVC) sink due to increased density, which also increases the settling velocity in riverine and lake ecosystems. Biological degradation, chemical oxidation, and mechanical friction encourage surface heterogeneity by cracks, scratches, and pores formation making microplastics less hydrophobic and buoyant and inducing micro-organisms colonization [134–136]. In an aquatic setting, the suspended sediments, clay minerals, and metal oxides also get adsorbed at microplastics' surface, other than micro-organisms, and form heterogeneous aggregation, leading to the settling of microplastics in water [137,138]. At the same time, microplastics remain suspended on the water surface because of the surface adsorption of suspended particles and sediments [139].

5. Natural Phenomena Governing Transport of Microplastics in River Environs

In an aquatic setting, plastics either float or suspend, which get transported for a long-time span (from days to years). Several studies have modeled the transport of plastic debris in different aquatic ecosystems across the globe using different numerical models, such as Lagrangian, two-way particle tracking, PELETS-2D, ARIANE, Lagrangian–Markov chain, MEDSLIK-II oil spill code, TrackMPD [42,140–145], tracers and GPS [146], and more. In addition to marine environments, numerous researches have documented microplastics transport in the rivers, such as the Seine River, Paris [147,148], Yangtze River, China [94,119,149], Venoge River, Switzerland [120], Ganga River, India [17,33], Rhine River, Germany [95], Lawrence River, Canada [104] and Danube River, Austria [150,151]. Microplastics pollution in rivers is highly heterogeneous, and therein, various factors underpin the lack of consistency in their observed abundance pattern [17,33,95].

River hydrological characteristics, such as bed-forms, flow velocity, water-level, tidal current, and overall discharge, influence the flow of plastic debris [68,152]. Similarly, the river morphological characteristics, such as vegetation intensity, slope, dams, barrages, reservoirs, also govern the fate and transport of microplastics in river environs [34,115,153–155]. For example, a decrease in river flow velocity decreases the abundance of microplastics [156], and flooding events can potentially increase the transport and aggregation of microplastics [157]. Weideman et al. [158] observed low microplastics abundance in the pre-flooding events, whereas large abundance after storm/flooding at the downstream side. Under horizontal transport conditions, aquatic or riparian vegetation retain microplastics and allow them to settle as flow velocity reduces [154,159].

Nizzetto et al. [66] described that microplastics are transported by river flow regimes and flooding events; however, sedimentation is governed by the shape, size, and density of microplastics. For example, in the Gota River, Sweden, higher density and large-size microplastics settle down at the river bottom, whereas microplastics with densities close to 1.0 g cm^{-3} float over the surface, and therefore, they are transported further to the marine ecosystems [160]. In rivers, the fate and transport of microplastics are governed by the presence of constructed structures such as dams and reservoirs, a large number of microplastics is getting retained due to sedimentation [10,34,155]. In contrast, the low flow zones in rivers (i.e., lower energy zone) retain micro- and nano-sized plastic particles and gradually settled down [11,77,153]. Therefore, artificial structures, such as dams, reservoirs, groynes, and guiding walls reduce the river flow that enhances the settling conditions of microplastics in the river bed [149,161].

Fragmentation and degradation are other major sources for the transport and sedimentation of microplastics in the riverine ecosystem [162]. Fragmentation is encouraged by microplastics degradation, hydrolysis, physical abrasion, and photo-oxidation [163,164]. As flocculation is the main factor of sediment transport [38], it plays a significant role in microplastics transport towards the sink. The river sediments are long-term reservoirs for microplastics accumulation, depending upon the characteristics of overlaying bed materials [79,118]. Sedimentation led to aggregation, interactions with organisms, and biofouling of microplastics. Biofouling enhances the particle density, i.e., more settling, while degradation decreases particle mass, which makes microplastics more buoyant in the river water [165,166]. Fragmentation, degradation, and biofouling influence settling rate of microplastics, in which fragmentation and degradation take longer residence time than biofouling in the river water [160].

Microplastics become suspended and are transported in the aquatic environment, depending on the river morphology and plastic characteristics. Ockelford et al. [79] coined the remobilization of microplastics in fluvial sediments, which drive the transfer of microplastics from the active layer, i.e., the upper layer of the sediment bed from where plastic particles are transferred by the river flow (Figure 2). The active layer becomes completely disturbed during flooding events (e.g., turbulent storm flow) across the rivers and consequently releases microplastics. Ockelford et al. [79] also explained the mechanism through storm hydrograph and excess critical shear stress of the median grain sizes with thresholds (excess critical shear stress, i.e., τ^*/τ^*_c where τ^* is the dimensionless shear stress and τ^*_c is the critical dimensionless shear stress for the median grain size, D_{50}), where the sediment bed transforms from the sink to source and source to sink for microplastics with respect to the flood wave. Laminar and turbulent flow induce critical shear stress, in which uneven riverine bottom surfaces can play a significant role in the resuspension of microplastics. At the starting point of the rising limb (τ^*/τ^*_c up to 0.9, i.e., first threshold), the sediment bed initially undergoes armoring, then stabilizes the bed surface while limiting the microplastics release. As the flow increases, the sediment bed becomes unstable ($\tau^*/\tau^*_c > 0.98$) and discharges a significant quantity of microplastics. Lastly, the final threshold ($1.26 < \tau^*/\tau^*_c < 1.35$) signifies the maximum transport of microplastics, and it occurs at the peak discharge (Figure 2). Therefore, Ockelford et al. [74] also reported that the maximum flux of microplastics occurs during the rising limb or in the early part of the flood. After the peak discharge, the storm flow attenuates exponentially as the active layer depth decreases irrespective of falling limb duration and returns from sink to the pre-flood level, resulting in less microplastics at watershed outlets. In river sediments, remobilization of microplastics is also known as microplastics erosion, depending upon the critical shear stress in-between the range of 0.002–0.233 N m^{-2} at higher flow velocities [74,167].

Tolhurst et al. [168] stated that bed-load, resuspension, and deposition of pellets under benthic shear environments are considered under laminar flow conditions. Microplastics experience rolling, sliding or saltation, and suspension at the bed-load depending upon their shear velocity, critical erosion velocity, and depositional shear velocity, respectively.

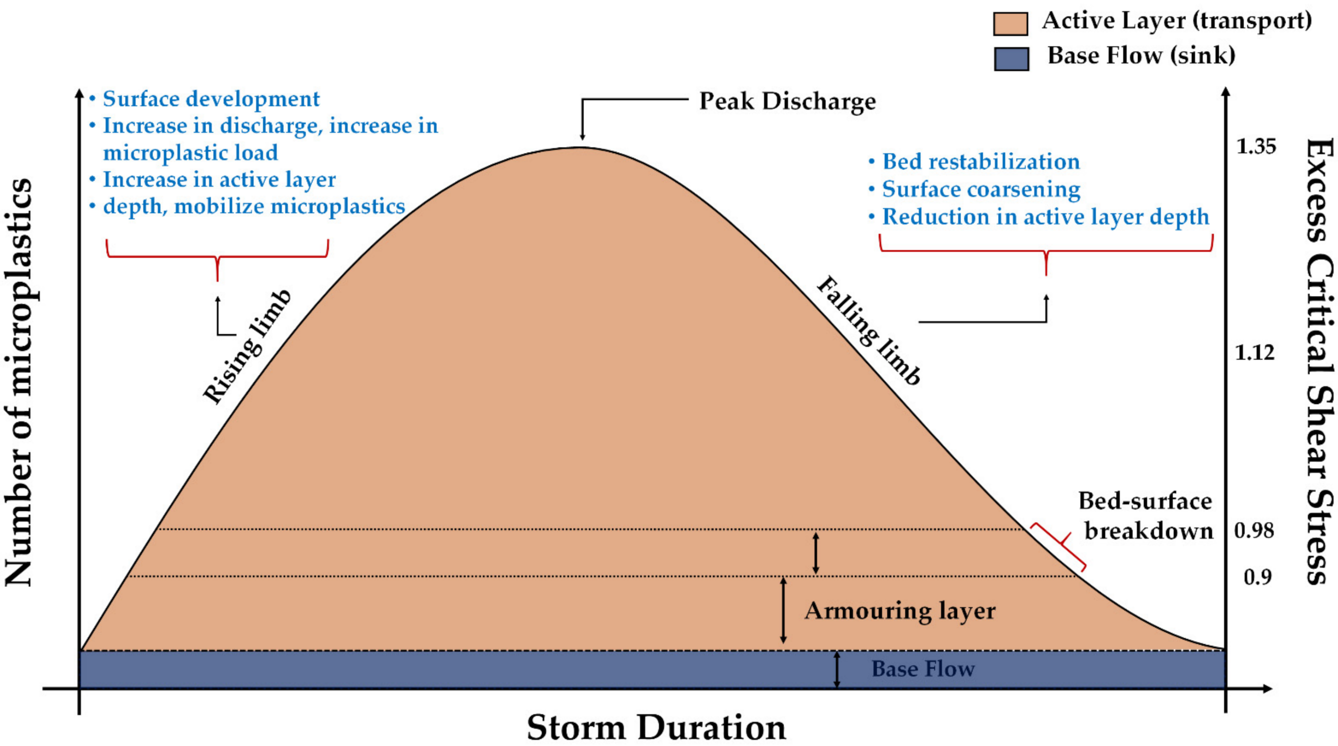

Figure 2. Proposing hydrograph for microplastics transport in river ecosystem and their relationship with various shear stresses of plastic particles.

In general, as stated above, sedimentation due to the influence of gravity force is a dominant mechanism for settling of microplastics. Microplastics transportation in the river is influenced by downward movement and the longitudinal direction of the advective flow of plastic particles [77,95,169,170]. Therefore, in the river bed, microplastics can be accumulated or translocated into the hyporheic zone, which may ultimately be deposited in the aquifer [118].

6. Current Progress on Microplastics Pollution Using Numerical Simulations

In-depth investigation of microplastics movement in the riverine ecosystem is based on mathematical/numerical model of fluid mechanics under different hydrodynamic settings (Table S1) [11,46,53,66,171–176]. The fundamental numerical models can simulate and estimate the transport of microplastic, as these fundamental numerical models are able to analyze the trajectory of microplastics in different aquatic settings. Numerical modelling for monitoring microplastics pollution could be a promising tool in the view of a thorough conceptualization of the riverine microplastics dynamics in a holistic manner. Only a few have provided theoretical background and conceptualized the transport mechanisms for investigating the fate of microplastics in aquatic settings [15,41,70,72,74,121,126,163,177,178] (Table 1). Isachenko [178] proposed a stochastic numerical model for determining the transport, especially terminal velocity depending upon the microplastics properties, such as diameter, density, shape, etc. and river flow characteristics, such as water density and viscosity based upon field observations, as follows:

$$V_S = f\left(d,\ \rho_p,\ csf,\ \rho,\ v_o\right) \quad (1)$$

where f is the function of terminal velocity, which depends on the independent variables such as particle parameters (d), particle density (ρ_p), and Corey shape factor (csf), water density (ρ), and water viscosity (v_o).

6.1. Floatation

Floatation is a typical procedure based on theories of diffusion and sedimentation for separating micro-sized plastics from sediments. For floatation, Stokes' law validates only when the flow regime follows the laminar flow or convective flux dominates over the diffusive flux. In general, the convective flux and laminar flow for extraction of meso- and micro-sized plastics are valid for floatation, determined by the Peclet number and Reynolds number [179].

$$\mathrm{P_e} = \frac{vL}{D} \gg 1$$

$$\mathrm{R_e} = \frac{v\rho d}{\eta}\ 0.1$$

where $\mathrm{P_e}$ represents the Peclet number, v is convective velocity, L denotes the characteristics length for floating plastic particles, and $\mathrm{R_e}$ highlights the Reynolds number.

6.2. Drag Coefficient and Settling Velocity

Drag coefficient and settling velocity are two fundamental properties for relating the plastic particle movement in the aquatic setting [72,74]. The terminal settling velocity of fine particles is estimated by balancing the net force from gravitational, buoyancy, and fluid drag forces equal to zero. Then, fluid drag ($\mathrm{F_D}$) can be expressed in drag coefficient and terminal settling velocity for fine particles. Stokes [180] provided a theoretical model for terminal settling velocity (V_T) and drag coefficient ($\mathrm{C_D}$). However, Stokes' law did not include the effect of hydrophobicity on plastic particles, and it is valid for a very low Reynolds number ($\mathrm{R_e}$ < 0.1), assuming the force of inertia can be ignored, which correlates the drag coefficient and terminal settling velocity for fine particles only. For higher Reynolds numbers, correlations between drag coefficient and terminal settling velocity cannot be established theoretically. Therefore, empirical correlations have been established for a wide range of Reynolds numbers to evaluate the influence of surface hydrophobicity by considering the effect of gravity and buoyancy, including interfacial tension (i.e., surface free energy) of particles. Modified Stokes' law, considering surface wettability, confirmed that the hydrophobicity has a significant impact on the settling velocity of particles, only when $d^* = (\Delta g/v^2)^{1/3}d < 2$ and $\mathrm{R_e} < 0.35$. Moreover, higher hydrophobicity of glass beads resulting in large settling velocity with low drag coefficients caused by micro-fluidicity for the same particle diameter [72]. Similarly, Waldschläger and Schüttrumpf [70] provided adjusted formula (as shown in Table 1) for settling and rising velocity under different drag coefficients associated with Reynolds number, which can be suitable for different shapes, like foams, fragments, and pellets. Interestingly, no such distinctions in their shape have been observed for settling and rising velocities observed for micro- and macro-plastics in the range of 0.16 to 3.52 cm $\mathrm{s^{-1}}$ and 0.18 to 19.85 cm $\mathrm{s^{-1}}$, respectively. Therefore, observed slower velocities of rising and settling might be due to changes in surface properties, such as high roughness and increase in the surface area resulting from microplastics weathering [74]. In benthic environments, the settling velocities for pellets are in the range of 20 to 70 mm $\mathrm{s^{-1}}$; pellets of higher density have faster settling velocities [41]. Further, Ballent et al. [42] also observed the sinking velocity of 28 mm $\mathrm{s^{-1}}$ for high-density plastic particles with an average size of 4.7 mm. Therein, Chubarenko et al. [51] observed that heavy microplastics takes more than 18 h to settle in the marine environment, whereas low-density plastic particles, polyethylene fibers take 6–8 months for sinking in the euphotic zone, and spherical particles can be retained on the water surface for 10–15 years. Whereas, in the laboratory experimental investigation, settling velocities for different density microplastics are in the range of 1 to127 mm $\mathrm{s^{-1}}$ [43,45,181].

For rising velocities, microplastics sampled in North Atlantic subtropical region have positive buoyancy of velocity, 1 to 43 mm s^{-1} [177,182,183].

Table 1. Theoretical numerical models for understanding transport of microplastics.

Model	Description	Limitations/Advantages	References
Floatation	Convective velocity V expressed by Stokes' law: $V = \frac{d^2 a \Delta\rho}{18\eta}$	Assumption: Plastic particles to be spherical in shape; For floatation, Stokes' law validates only when the flow regime follows the laminar flow and convective flux governs over diffusive.	[179]
Diffusion	Stokes-Einstein equation: $D = \frac{2kT}{6\pi\eta d}$ $\mathrm{P_e} = \frac{VL}{D} \gg 1$ $\mathrm{R_e} = \frac{V\rho d}{\eta} 0.1$	Assumption: Plastics particle to be micro-sized; Convective flux and laminar flow for extraction of meso- and micro-sized plastics are valid for floatation, determined by the Peclet number and Reynolds number.	[179]
Terminal Velocity	Dietrich formula: $\mathrm{V_T} = \sqrt[3]{V_* \frac{\rho_s - \rho_l}{\rho_l} g v_o}$	The net force on particles is zero. Reynolds number < 1. Particles must follow the principle of physical similarity.	[43,45,178,184]
Drag Coefficient and Settling Velocity	$\mathrm{F_D} = \frac{1}{8}\, \mathrm{C_D} \pi d^2 \rho_l V_\mathrm{T}^2$ $V_T = \frac{gd^2}{18\eta}\,(\rho_s - \rho_l)$ $\mathrm{C_D} = \frac{24}{\mathrm{R_e}}$	The terminal settling velocity of fine particles states when the net force of three gravitational, buoyancy, and fluid drag forces is equal to zero. Hydrophobicity is not considered.Stokes' law is valid for a very low Reynolds number ($\mathrm{R_e} < 0.1$).	[72,180]
	Drag coefficient for the following: Settling particles: $C_{D,\, sp} = \frac{3}{csf \times \sqrt[3]{R_e}}$ Rising particles: $C_{D,\, rp} = \left(\frac{20}{\mathrm{R_e}} + \frac{10}{\sqrt{\mathrm{R_e}}} + \sqrt{1.195 - csf}\right) \times \left(\frac{6}{P}\right)^{1-CSF}$ Settling and rising velocity: $V_x = \sqrt{\frac{4}{3}\, \frac{d_{equi}}{C_D} \left\| \frac{\rho_s - \rho_l}{\rho_l} \right\| g}$	For $\mathrm{R_e} < 0.5$, $\mathrm{C_D} = \frac{24}{\mathrm{R_e}}$ For $0.5 < R_e < 103$ $\mathrm{C_D} = \frac{24}{\mathrm{R_e}} + \frac{5}{\sqrt{\mathrm{R_e}}} + \frac{2}{5}$ For $103 < \mathrm{R_e} < 2 \times 105$ $\mathrm{C_D} = 0.44$	[185]
Modified version for Drag Coefficient and Settling Velocity	$E_{Ol} = \frac{gd^2\,(\rho_s - \rho_l)}{\gamma_{sl}}$ $V_T = \frac{gd^2}{18\eta}\,(\rho_s - \rho_l) \quad \{e^{(-0.3+0.18\theta-0.02\theta^2)}$ $+(2.3\theta + 1.32)e^{-\sqrt{E_{Ol}}/[0.01\theta^{(-0.99)}}\}$ $\mathrm{C_D} = \frac{24}{\mathrm{R_e}}\{e^{(-0.3+0.18\theta-0.02\theta^2)}$ $+(2.3\theta$ $+1.32)\, e^{-\sqrt{E_{Ol}}/[0.01\theta^{(-0.99)}}\} --$ Dimensionless diameter, d^* = (Δg/v2)1/3d	Valid for $d^* < 2$ and $\mathrm{R_e} < 0.35$. Reynolds number to evaluate the influence of surface hydrophobicity by considering the effect of gravity and buoyancy, including interfacial tension (i.e., surface free energy) of particles. Consideration for surface wettability resulting in interfacial tension on particles.	[72]
Turbulent vertical mixing	Using Stokes' law: $\mathrm{F_D} = \frac{1}{8}\, \mathrm{C_D} \pi d^2 \rho_l V_\mathrm{T}^2$ $V_T = \frac{gd^2}{18\eta}\,(\rho_s - \rho_l)$ $\mathrm{C_D} = \frac{24}{\mathrm{R_e}} + \frac{5}{\sqrt{\mathrm{R_e}}} + \frac{2}{5}$ Vertical movement: $U_z = V_T + \xi\sqrt{\frac{2K_z}{\Delta t}}$	Assumption: At a high Reynolds number, terminal velocity is at a steady state. ξ is a random coefficient ranging from −1 to 1 for turbulent conditions.	[52]
Shields Parameter	$\theta = \frac{\tau_o}{(\rho_s - \rho_l)gd}$	Assumption: Shields diagram for uniform sediments Critical shear stress in the range of 0.002–0.233 N m^{-2} denotes erosion beginning. Force of lift and drag higher than resistance.	[74]

6.3. Terminal Velocity of Microplastic

Terminal velocity describes the transport behavior of particles (e.g., either rising or falling) under steady-state or stagnant water conditions, assuming the total forces acting on particles from all directions are properly balanced [178]. Terminal velocity of particles depends upon the difference between the density of particle and the fluid, as rising velocity (i.e., positive buoyancy) is equal and opposite to settling velocity (i.e., deposition) of the particles. According to Stokes' law, terminal particle velocity is valid for laminar flow, i.e., low Reynolds number ($R_e < 1$) [185]. Isachenko [178] simulated that rising and settling velocities for plastic particles are 10 cm s^{-1} and 15 cm s^{-1}, respectively, using the Dietrich formula (as mention in Table 1). It was also predicted that the terminal velocities are close to the above-estimated value for spherical microplastics particles, whereas there would be huge discrepancies for irregularly shaped microplastics [43,45].

6.4. Shields Parameter

The minimum flow velocities required for the first microplastics movement are described by critical shield shear stress, which depends on the fluid density. In the Shield diagram shown in Figure 3, Waldschläger and Schüttrumpf [74] assumed uniform microplastics eroded as rolling, sliding, and saltating (i.e., intermittent bouncing) conditions with natural sediments after achieving critical shear stress under bed-load transport. Microplastics associated with sediment grains encourage erosion depending upon the critical shear stress. For uniform grains, critical shear stress was observed as 0.002–0.233 N m^{-2} for eroding the microplastics, whereas it is difficult to predict erosion behavior for non-uniform sized grains. On the far side, the hiding exposure effect shows significant erosion as large grains are possibly exposed via laying over the smaller-sized microplastics. Critical shear stress is strongly influenced by the density, diameter, and shape of microplastics which is expressed as Shields Parameter [42]. Considering densities and shape into account, high-density plastic particles have lower Shield parameters and higher Reynolds numbers. Contrastingly, low-density plastics have lower Reynolds numbers ($R_e < 1$) and possess higher Shield parameters (>0.1), resulting in no motion in the Shield diagram. Therein, with increased particle diameter, Reynolds number also increases and influences the erosion ultimately [74].

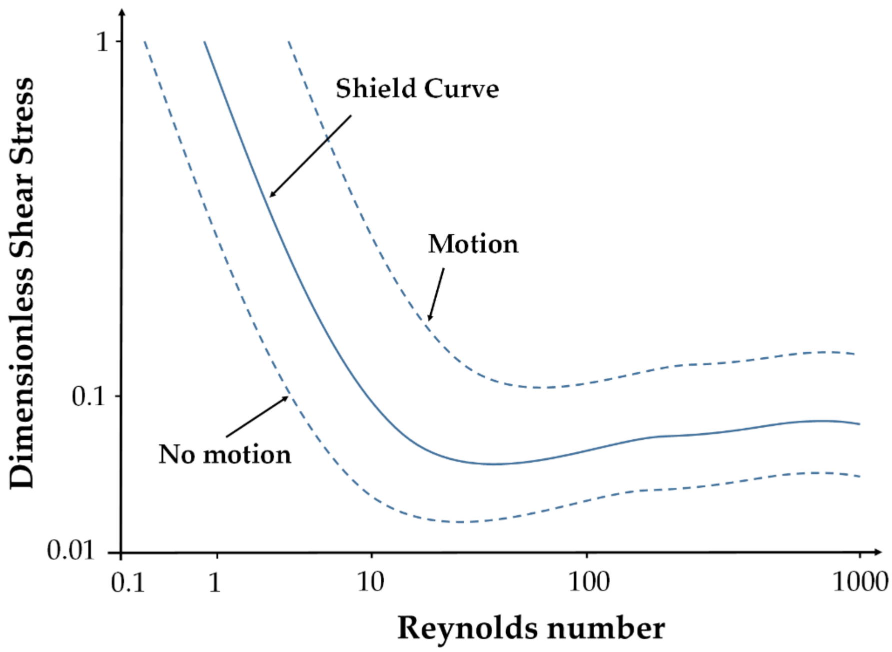

Figure 3. Relationship between dimensionless shear stress and Reynolds number for analyzing microplastics transport in riverine ecosystems.

7. Conclusions and Recommendations for Future Research

Plastic pollution is a global and pervasive problem in the riverine ecosystem. This review has highlighted the fate of microplastics in the river ecosystem and the processes governing their transport and sedimentation. There is a critical need to further unravel the role of climatic and realistic field conditions on transport and sedimentation of microplastics in ecologically sensitive systems such as rivers, wetlands, and so on. It is important to account for empirical investigation under the influence of environmental conditions, biofilm colonization, and particle dimensions. We found that the microplastics interact well with natural ecosystems, and thus feedbacks that govern their fate and transport, particularly in terrestrial and aquatic ecosystems, are under increasing threat from development and climate change. We have identified the key gaps in our current understanding that warrant further exploration and research. Therefore, the overall recommendations for future research are specified as follows:

- Spatial and temporal mapping for storage and transport of microplastics is needed to understand the extent of microplastics pollution in the river streams under varying climatic and realistic conditions [77,155,186];
- In river flow conditions, it has been observed that microplastics transport vertically down depending upon the density and shape of microplastics in the water profile [187,188]. However, impacts on biogeochemical cycle and plastics dynamics were not considered until now for determining the microplastics transport;
- The current concern needs to quantify the effect of rheological behavior and viscosity under Newtonian and non-Newtonian fluid conditions on settling velocity and drag force of microplastics [189];
- So far, the influence of environmental conditions, such as temperature cycle, especially cold or warmer temperature, on the transport of nano- and micro-plastic in natural environmental conditions is unknown;
- It is recommended to consider the concept for hydraulic jumps using a Froude number on the transport of microplastics in riverine ecosystems;
- The transport of microplastics in the water column should be assessed along with the concurrent movement of nutrients and other pollutants that mimic the riverine environment;
- Further research on microplastics may affirm insights into how much time a particle takes to remain in suspension and how the vertical distribution of a particle occurs in the riverine ecosystem under different laminar and turbulent flow conditions;
- Biofouling and colonization sensitivity of different microplastics need to be investigated in relation to organisms and permanence of plastic in the riverine and other ecosystems, which should be supported with best statistical tests to compare accumulation areas.

Microplastics are heterogeneous hazardous compounds and possess distinct behavior because of their density, shape, and size in the riverine environs. Therefore, quantifying and predicting the fate and transport of microplastic particles in riverine ecosystems allows scientists, researchers, ecologists, environmental conservationists, hydrologists, policymakers, and other stakeholders to understand plastics pervasive problems at the regional and global scale and can be helpful in monitoring microplastics in aquatic ecosystems.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/w13192710/s1, Table S1: Sources and effect of environmental conditions on the aggregations of microplastics.

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Abbreviations

V: Convective velocity, m/s; d: Diameter of the plastic particle, m; a: Centrifugation m/s^2; g: acceleration due to gravity, m/s^2; η: Dynamic viscosity, Pa.s; v_o: Kinematic viscosity, m^2/s; V_T: Terminal velocity, m^2/s; D: Diffusion coefficient; csf: Corey shape factor, according to Corey [190]; k: Boltzmann constant, T: Absolute temperature (K); P_e: Peclet number; τ_o: Shear stress, N/m^2; R_e: Reynolds number; F_D: Drag force, $C_D \pi d^2 \rho_l V_T^2/8$; F_G: Force of gravity, $\pi \rho_s g d^3/6$; C_D: Drag coefficient, $4(\rho_s - \rho_l)gd/\left(3\rho_l V_T^2\right)$; L: Characteristics length for floating plastic particles, m; ρ_l: Density of the solution, kg/m^3; ρ_s: Density of the solid particle, kg/m^3; $\Delta\rho$: Difference in the density of particle and separation solution, kg/m^3; E_{Ol}: Dimensionless number, relationship between gravity, buoyancy and interfacial tension; γ_{sl}: Surface free energy of the particle, J/m^2; K_z: Vertical turbulent mixing coefficient; U_z: Vertical mixing movement; V_*: Dimensionless terminal velocity; ξ: Random coefficient (vary from −1 to 1); θ: Shield parameter.

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