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FOCUSED REVIEW

Behavior of Microplastics in Inland Waters: Aggregation, Settlement, and Transport

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Abstract
Inland waters are the main medium transporting microplastics to the ocean. Aggregation, vertical settlement, and horizontal transport will occur when microplastics enter the inland waterbodies. This paper reviews these behaviors of microplastics in inland waters and their influencing factors. The aggregation of microplastics were divided into homogeneous aggregation and heterogeneous aggregation, which are critical for the settlement of microplastics. The settlement of microplastics in inland water bodies is influenced by microplastic properties (size, density, and shapes) and environmental conditions (microorganisms, sedimental properties, hydraulic conditions, and so on). Horizontal transport of microplastics in water is influenced by hydrologic conditions, rainfall, river morphologies, dams, vegetation, etc. Future perspectives including laboratory simulations and numerical models involving multiple factors, the behaviors of degradable plastics, and the influence of hydrologic conditions have been proposed.

Keywords Microplastic · Inland water · Aggregation · Settlement · Transport

Introduction

Nowadays plastic is widely used due to its superb properties such as low cost, versatility, and durability (Zhang et al. 2020b). In recent years, the environmental behavior of tiny plastic debris, known as 'microplastic' (particle size less than 5 mm), has been extensively studied, especially in the marine environment (Liu et al. 2019a; Duan et al. 2020; Li et al. 2020a). Since a substantial fraction of marine microplastics are originated from land-based sources and enter the sea via rivers, the transport of microplastics in the inland waters has attracted increasing attention (Schmidt et al. 2017; Welden and Lusher 2020).

A significant portion of land-based plastic is transported to the ocean by rivers (Lechner et al. 2014). According to Schmidt et al. (2017), the global amount of plastic debris entering the ocean from rivers ranges from 0.41 to 4×10^6 t/y. These plastics may eventually break down into microplastics and influence the marine ecosystem. Once microplastics enter the ocean, it is unrealistic to collect and clean them up. The only practical solution is to limit the emission of microplastics to the inland waters and control the process of their transport to the ocean (Nizzetto et al. 2016). In the inland waterbodies, the transport and fate of microplastics may be determined by their hydrodynamic behaviors, especially aggregation, settlement, resuspension, and horizontal transport (Fig. 1). These behaviors are affected by many factors (e.g., properties of microplastics, hydrologic/hydraulic conditions, etc.), which may eventually influence the transport of microplastics to the ocean.

In recent years, occurrence of microplastics in lakes, rivers, and reservoirs has attracted increasing attention (Zhang et al. 2018; Piehl et al. 2019), and these advances make it possible to evaluate the role of major hydrodynamic behaviors in the fate of microplastics. The purpose of this paper is to review the factors affecting the behaviors and fate of microplastics in the inland waters. Aggregation, settlement, and horizontal transport of microplastics have been discussed and perspectives of future study have been proposed.

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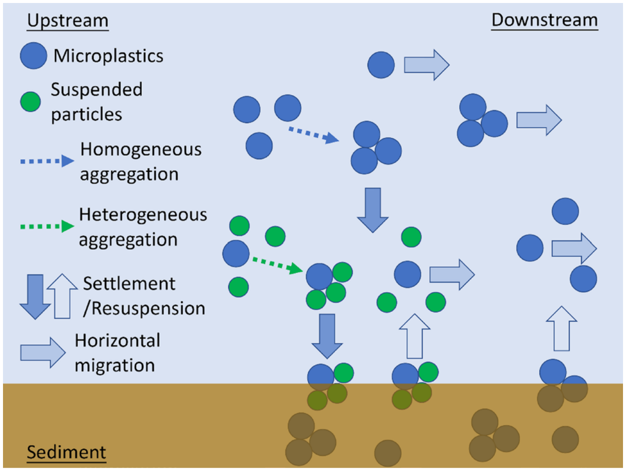

Fig. 1 Behaviors of microplastics in inland waters

Aggregation

After entering inland waters, microplastics do not always exist as single particles, some of which will aggregate and ultimately have different fates and ecological risks (Li et al. 2018). Aggregation of microplastics is a critical physicochemical process dominating the transport (including vertical and horizontal) and overall fate of microplastics in waterbodies (Wang et al. 2021). Aggregation can be divided into two types: homogeneous aggregation, which refers to the aggregation of similar particles (e.g., microplastic–microplastic); heterogeneous aggregation, which refers to the aggregation of dissimilar particles (e.g., microplastic–non-plastic particles) (Hotze et al. 2010; Besseling et al. 2017). Derjaguin–Landau–Verwey–Overbeak (DLVO) can be used to explain the aggregation of microplastics. According to this theory, aggregation of microplastics is determined by the balance between two opposing contributions: attractive van der Waals forces and electrostatic repulsive forces (Hotze et al. 2010; Li et al. 2019). However, the DLVO theory ignored the impact of non-uniformity on the interaction surface (Cai et al. 2018), which may result in an inaccuracy of predicting the aggregation of nanoplastics in water.

Homogeneous Aggregation

Homogeneous aggregation is the aggregation that occurs between the same type of particles. In this paper, it refers to the aggregation between microplastics. The homogeneous aggregation of microplastics in inland waters is affected by the properties of microplastics (e.g., the particle size and aging degree) and physicochemical properties of water (e.g., metal ions, pH, surfactant, and NOM).

The properties of microplastics are related to the efficiency of homogeneous aggregation. Under the same water environment conditions, the microplastics with larger particle size have greater stabilities and less aggregation than those with smaller particle size (Song et al. 2019). Aging may change the properties of microplastics, which can also affect the homogeneous aggregation. It has been shown that aging process inhibited polystyrene nanoparticles (PSNPs) aggregation by increasing the negative charge on particle surface and the content of organic matter in the NaCl solution (Liu et al. 2019b). Furthermore, aging can induce the formation of carbonyl groups on the surface of the microplastics, which can improve the stabilities of the microplastics in water (Mao et al. 2020). However, Wang et al. (2020) found that ultraviolet irradiation reduced the negative charge on the surface of PSNPs, thus increased the aggregation of PSNPs.

The influence of water physicochemical properties (e.g., metal ions and pH) on the aggregation of polystyrene microplastics could be due to steric effects, such as changing surface charge and/or steric repulsion (Lu et al. 2018; Mao et al. 2020). For example, high valence ions (e.g., Fe^{3+}) compress the electrostatic double layer more effectively than low valent ions (e.g., Na^{+}), and the aggregation effect increases with increasing ionic strength (Lu et al. 2018; Mao et al. 2020; Cai et al. 2018). In addition, divalent cations showed greater effects on the aggregation than divalent anions (Lu et al. 2018).

Electrolytes concentration can also influence the aggregation profiles of microplastics. Critical coagulation concentration (CCC), the electrolyte concentration for the transition from unfavorable to favorable aggregation (Petosa et al. 2010), have been used to evaluate particle stabilities under various conditions (Mao et al. 2020). For example, Li et al. (2018) found that, below CCC, the aggregation attachment efficiencies of micro-PS increased with increasing electrolyte concentrations. However, at pH 6.0 (in NaCl), the aggregation attachment efficiencies of micro-PS were independent of the electrolyte concentration above CCC.

In general, at low pH (<3), the electrostatic repulsive force is weak, which leads to larger hydrodynamic diameters of microplastics and eventually obtains more aggregation. However, natural water has a much higher pH (mostly 6.5-9), at which the hydrodynamic diameters of microplastics remain constant and may induce partial disaggregation due to the increase of electrostatic repulsive force (Lu et al. 2018; Wang et al. 2021). As a common NOM in water, humic acid (HA) has abundant oxygenated functional groups, such as carboxylic and hydroxyl, which can influence the colloidal stability of microplastics (Wilkinson et al. 1997; Lu et al. 2018). But the HA-influenced aggregation of microplastics can be affected by pH. Due to the steric hindrance effect, HA inhibited the aggregation of microplastics at low pH but had no effect at high pH (> 4). HA also showed different effects on microplastics aggregation together with cations. In the presence of metal ions, for example, the inhibitory effect of HA on aggregation is weakened and affected by the order of addition (microplastics + HA + metal ions). These results were obtained at relatively low pH (5.0), which only occurs in acidic wastewater (Lu et al. 2018). Surfactants are widely used as stabilizers for colloidal particles, but surfactants do not always improve the stability of colloids. For example, high concentrations of surfactants can lead to the loss of stability of polystyrene colloidal particles (Jódar-Reyes et al. 2006), indicating that surfactants may influence the aggregation of microplastics in water environment.

Heterogeneous Aggregation

Heterogeneous aggregation of microplastics in inland waters is more important than homogeneous aggregation of microplastics, which means the aggregation between microplastics and other solid constituents such as organisms, clay minerals, metal oxides, proteins, and so on (Wang et al. 2021). Microplastics are more likely to aggregate with natural constituents, which is generally much larger than microplastics (Besseling et al. 2017; Galloway et al. 2017; Li et al. 2019). Recently, most studies focused on the aggregation between organisms and microplastics. For example, an estimation of the heterogeneous aggregation of polypropylene (PP) microplastics was approximately 50%, and 50% of these aggregates were comprised of microalgae, indicating that organisms might play an important role in the hetero-aggregation of microplastics in water (Lagarde et al. 2016).

Microplastics can provide surfaces for the colonization of microbial communities and the formation of biofilms (Miao et al. 2019). The colonization of the microorganisms on microplastics, which is influenced by many factors including microplastic properties, algal species, and environmental conditions, is an important factor affecting heterogeneous aggregation of microplastics. For example, the growth of algae on microplastics is affected by the composition (i.e., type of polymer) of microplastics. Lagarde et al. (2016) studied the interactions between two types of microplastics and freshwater algae. The results showed that a composite of microalgae and extracellular polymers formed on the PP microplastics surface after 20 days. In contrast, this aggregation was not observed on the surface of high-density polyethylene (HDPE) microplastics. Mechanical friction, chemical oxidation (including ultraviolet radiation), and biological degradation generally make the surface of microplastics to have more scratches, cracks, and micropores (Gong et al. 2019; Liu et al. 2020), which becomes less hydrophobic and more neutrally buoyant, and is conducive to the colonization of microorganisms (Lobelle and Cunliffe 2011). The shape of microplastics may also affect the aggregation with algae. The aggregation between plastic microbeads and algae was observed to be rapid (Möhlenkamp et al. 2018), whereas few studies have compared the aggregation between different shapes of microplastics and algae.

Aggregation of microplastics and algae also depends on algal species. Long et al. (2015) compared the aggregation of polystyrene microbeads with two marine algal species (*Chaetoceros neogracile* and *Rhodomonas salina*), the results of which showed that *C. neogracile* aggregates were generally larger and stickier than those of *R. salina*. The freshwater systems are also rich in algae, and their ability to colonize microplastic surfaces may also be related to their species. It has been found that several types of algae (such as Cyanobacteria, Chlorophyta, Cryptophyta, etc.) colonize on the surface of microplastics in freshwater systems (Chen et al. 2019). A possible reason for the impact of algal species is the production of extracellular polysaccharides (EPS), which provides an attractive force (Eboigbodin and Biggs 2008), maintains algal cells together and attaches aggregates microplastic surfaces. But EPS is not species-specific, which is also dependent on algal age, strain and/or external conditions (Allard and Tazi 1993).

Compared with the marine environment, freshwater generally has a higher trophic conditions and weaker turbulence, which are beneficial for the formation of biofilm on microplastics (Wang et al. 2018a; Chen et al. 2019). The growth of biofilm on the surface of microplastics, which is affected by environmental conditions (such as temperature, sunshine duration, ultraviolet radiation, nutrient levels, turbulence, etc.), may strongly affect the aggregation kinetics of microplastics (Leiser et al. 2020). For example, higher temperature and longer sunshine hours usually result in higher biomass of biofilm due to the faster growth of microorganisms and the increase in phosphorus release from the sediment (Chen et al. 2019; Kaiser et al. 2017). Exposure period and water depth also can influence the formation of biofilm. Tu et al. (2020) found that longer exposure duration increased biofilm formation on microplastics, whereas greater water depth decreased the formation.

In addition to microorganisms, other particles in the inland water environment such as clay minerals and metal oxide nanoparticles (e.g., Fe_2O_3) can also aggregate with microplastics (Oriekhova and Stoll 2018; Dong et al. 2019). Microplastics with small particle size can adsorb on the surface of large suspended sediments and form heteroaggregates, which may cause a rapid settle down of the suspended microplastics in the water. However, some large plastic particles suspended on the water surface will not settle due to the surface adsorption of suspended particles (Li et al. 2019).

Settlement and Retention

After entering freshwater environment, microplastics may sink into the sediments by the combined effects of buoyancy and gravity (Wong et al. 2020). Data obtained in previous studies have shown that the concentrations of microplastics in the sediments are significantly higher than those in the surface water (Su et al. 2016; Zhang et al. 2017). If the sediments of freshwater can retain more microplastics, the input flux of microplastics through rivers to the ocean will be reduced (Nizzetto et al. 2016). Freshwaters are considered one of the most complex systems regarding microplastics transport and retention (Horton and Dixon 2018), and therefore the settling behavior of microplastics in inland water environment is becoming a major concern.

Microplastic Properties

Particle size of microplastics has a dramatic effect on the fate of microplastics and the settlement behavior along the river (Besseling et al. 2017). A relative lack of plastic particles with sizes below 1 mm was found in the marine environment, which was speculated to be caused by size-selective sinks (Cózar et al. 2014). Settlement may be responsible for the loss of nano- and micro microplastic fraction, and the retention in inland water systems may be an important reason, which has been confirmed by a study using hydrodynamic model (Besseling et al. 2017). Their study also found that the relationship between the retention rate of microplastics in the sediment and the size of microplastics was not monotonous. For the particles between 100 nm and 10 mm, the sedimentation rate increased with increasing diameter. For the particles between 100 nm and 2 µm, increasing the diameter resulted in a reduced sedimentation rate of the heteroaggregates (Besseling et al. 2017). Hu et al. (2018) and Li et al. (2020b) found that amount of microplastics decreased in the sediments with increasing particle size when the size is larger than 0.5 or 1 mm. Eo et al. (2019) also found that, the abundance of microplastics increased as particle size decreased in the sediment, and then decreased below a specific size threshold. Due to the complexity of the physical environment (e.g., microplastics may aggregate), there may be differences between the experimental results and the numerical simulation. In the future, more simulations close to the real environment, including homogeneous and heterogeneous aggregation, are needed to study the settling rate of microplastics in the water environment.

Under the same conditions, microplastics with smaller sizes are more prone to aggregation than those with larger size (Wang et al. 2021). Most researchers believe that the aggregation can help the sedimentation of microplastics and the degree of aggregation also leads to a greater rate of sedimentation (Ballent et al. 2016; Möhlenkamp et al. 2018; Lagarde et al. 2016). Small microplastics has a higher degree of biofouling, which may induce the buoyancy of microplastics and result in faster settlement than the larger microplastics (Fazey and Ryan 2016). In addition, compared with larger microplastics, the size of smaller microplastics (mainly 20–200 µm) is similar to that of diatoms, which are easy to be grazed and digested by zooplankton, and thus resulting in deposition of microplastics in fecal pellets (Cole et al. 2016; Wang et al. 2018a). Under hydrodynamic turbulence, resuspension of microplastics deposited in sediment can return the overlying water and constitute an important source of microplastics in the water column (Eo et al. 2019). Waldschläger and Schüttrumpf (2019) found that microplastics with larger size rose rapidly, which also explained why more microplastics with smaller size were found in sediments.

However, large microplastics were also found in higher abundance in some sediments (Zhang et al. 2017). One reason is that there may be a higher amount of large size microplastics emitted to the surface water. Another reason is that the relatively weak hydrodynamic conditions and high trophic levels of water allow a rapid development of biofilm on the surface of the large plastic detritus and the biofouling leads to the sinking before they break down. Due to the limitation of separation, digestion, identification and quantification methods, the abundance of microplastics with small particle sizes in the sediments tends to be underestimated (Conkle et al. 2018; Prata et al. 2019), which provides a plausible explanation for the higher abundance of large microplastics than the smaller ones in the sediments.

After entering the water, the microplastics with the densities higher than water settle easily (Kaiser et al. 2017), which is why higher abundance of microplastics with low densities (< 1 g/cm^3) has been observed in surface water (Zhang et al. 2017). The concentrations of microplastics in rivers with low flow velocities and deep depth were found to vary in gradient with depth: the low-density microplastics gradually decreased from the water surface to the sediment, while those with high densities presented in an opposite gradient, except in very turbulent waters (Lenaker et al. 2019; Ma et al. 2020). However, high abundance of low-densities (lower than water) microplastics were also observed in the sediments (Ballent et al. 2016; Zhang et al. 2017). For example, high-density polyethylene (HDPE, 0.94–0.97 g/cm^3), low-density polyethylene (LDPE, 0.89–0.94 g/cm^3), and polypropylene (PP, 0.89–0.91 g/cm^3) have been widely observed in sediments (Nuelle et al. 2014). As we mentioned earlier, the colonization of microorganisms (e.g., algae) and the adsorption of solid particles may lead to an increase in the densities of the aggregates, which facilitates the settlement of microplastics in water. For example, the density of aggregated PP was measured as approximately 1.19 g/

cm^3, which is much higher than its initial density and may explain the high abundance of microplastics with low densities (Lagarde et al. 2016).

In water environment, many shapes of microplastics have been observed, including fragment, fiber, sphere, film, and pellet, among which the form of fiber and fragment accounts for the highest proportion in water and sediments (Li et al. 2020b). In most waterbodies, the abundance of fiber microplastics was higher than fragment (Fischer et al. 2016; Wang et al. 2018b). Through simulation experiment, Hoellein et al. (2019) found that the settling rate of fragment microplastics in fresh water was higher than that of fiber. However, irregular shapes of fragments may have secondary movements, which usually reduce the vertical settling velocities and sink more slowly than other shapes of microplastics with similar sizes (Waldschläger and Schüttrumpf 2019). Khatmullina and Isachenko (2017) measured the settling velocities in water of microplastics with three shapes, sphere, short cylinder, and long cylinder, and concluded that the particle shape can influence the settling velocities of microplastics. Moreover, the influence of shape only becomes pronounced when particles reach a certain size (Khatmullina and Isachenko 2017). Wang et al. (2018a) also found that the influence of shape on microplastics settlement might be influenced by size. In their study, fibers larger than 300 μm were the main microplastics isolated from river sediments, while microplastics smaller than 300 μm were mostly fragments.

Environmental Conditions

The settlement of microplastics in water can be influenced by the grazing of aquatic organisms. For example, some species of fish, tadpoles, and invertebrates ingest microplastics, which will eventually settle to the sediments along with excretion or debris (Kuśmierek and Popiołek 2020; Hu et al. 2018; Zhang et al. 2020b). The sizes of some small microplastics are similar to those of diatoms, which are the main prey of zooplankton, so these microplastics may settle along with the dead zooplanktons (Cole et al. 2016). The physiological properties, lifespans, the excretion rates of these organisms may influence the settlement of microplastics. For example, Hoang and Felix-Kim (2020) observed that it took longer duration for bent body fish to excrete polyethylene microbeads than straight body fish. Their study also found that the excreted microplastics were likely coated with intestinal fluid of fish, which is denser than the water and result in aggregation and deposition of microplastics.

The nature of the sediment influences the retention of microplastics. Fischer et al. (2016) found that the sediments rich in organic matter can act as a repository for microplastic debris over a prolonged period. Their study showed that the fiber concentration in Lake Chiusi sediments was higher than that in Lake Bolsena, which may be due to Lake Chiusi's higher eutrophication level and organic matter content. More retention of microplastics induced by high organic matter content in the sediments were also observed by Corcoran et al. (2019). In their study, the greatest amount of microplastics were identified in the sediment samples with the greatest amount of organic debris. In the same study, grain sizes of the sediments were found to be important factor affecting the retention of microplastics, and the greatest amount of microplastics were observed in the sediment samples with the finest grain sizes. In addition, the texture of the sediments also influences the retention of microplastics. The microplastics deposited in the sediments have a potential of resuspension, which is influenced not only by microplastic properties but also by the conditions of the sediment. The settled microplastics in loose sandy sediments are easier to resuspend and return to the overlying water (Fischer et al. 2016). Nevertheless, some researchers have found that the concentrations of the microplastics in sediments of Ottawa River was not significantly related to the particle size or organic matter content of sediments (Vermaire et al. 2017).

Hydraulic conditions can influence the settlement and resuspension of microplastics (Rao et al. 2020). There was a negative correlation between microplastic abundance and flow velocity in the sediments, and weak hydrodynamic conditions were favorable for microplastics deposition (Zhang et al. 2017). Microplastics were more abundant in surface (0–2 cm) sediments in calm water, while suspended forms increased when the current was more turbulent (Wu et al. 2020). In the intertidal area, a greater abundance of microplastics is usually observed in the surface sediment than at the deeper depth (Willis et al. 2017). An explanation is that some microplastics settle on the sediment surface at low tide but resuspend at high tide, so the microplastics cannot be permanently retained in deeper sediments (Wu et al. 2020). Wu et al. (2020) also found the resuspension of larger microplastics in the sediments of Yangtze Estuary requires stronger water flows, such as those occur during spring tides. Flooding events can mobilize the active layer of river sediments, which has the potential to induce large amount of release of microplastics from within the sediments (Ockelford et al. 2020). According to an estimation by Hurley et al. (2018), approximately 70% of the microplastics retained on the studied river beds in England was exported by flooding. During the rainy season, large amounts of water discharge and fast flow can induce resuspension of microplastics previously deposited in the river sediments. Wind is also an important factor influencing microplastics resuspension. Wind-driven mixing and oscillation of water can facilitate the resuspension of microplastics in the sediments (Fischer et al. 2016). In recent years, researchers has focused on climate change (e.g., the alterations in water temperature and wind disturbance) on the changes of current direction and velocity, which can influence the sediment resuspension and the release of microplastics in shallow lakes (Zhang et al. 2020c). In general, most laboratory studies on the settlement of microplastics were conducted under the condition of static water, whereas the settling behavior of microplastics in flowing water needs to pay more attention. Although the resuspension is one of the causes of the redistribution of the settled microplastics, the contribution of microplastics resuspension needs to be evaluated.

Horizontal Transport

In addition to settling to the bottom of lakes and rivers, a certain proportion of microplastics will be transported downstream and eventually enter the ocean. Therefore, it is meaningful to understand the dynamics of horizontal transport and distribution in the inland water systems (Nel et al. 2018). Previous studies have shown that a large amount of microplastics are retained during the horizontal transport, which is mainly affected by hydrological conditions of the rivers or streams.

Hydrologic Condition

Xiong et al. (2019) investigated the occurence of microplastics along the middle and lower reaches of the Yangtze River and found that certain amount of microplastics were retained in the waterways along the River. The horizontal transport of microplastics in rivers is influenced by many factors, including hydraulic conditions, rainfall, river morphology, dams, vegetation, etc. (Zhang et al. 2020a; Mani and Burkhardt-Holm 2020). For example, due to the strengthened hydrodynamics during the rainfall, microplastics in the sediments can resuspend and return to the overlying water, which facilitates the horizontal transport of microplastics (Flynn et al. 2018). Weideman et al. (2020) collected surface water samples along the Orange-Vaal River at the end of the rainy and dry seasons and found that small microplastics are particularly abundant in downstream during the low flow period before the rain-derived flooding, while more large-sized microplastics were found in downstream after flooding. River morphology can affect flow velocities and therefore influence the transport of microplastics. Positive relationship between high flow velocity and low microplastic abundance has been observed in urban river environments by Tibbetts et al. (2018). In Thames River, Canada, the sediment samples collected along the straight river channel contained less microplastics than those collected from the inner outer bends (Corcoran et al. 2019).

Construction and vegetation in rivers may influence the horizontal transport of microplastics by changing hydraulic conditions. Dams can also trap and retain microplastics, and researchers have found that microplastics particles accumulate behind dams over a long timescale (Watkins et al. 2019; Huang et al. 2020). However, Weideman et al. (2019) claimed that dams might not act as local sinks for floating microplastics or microfibers, which may be due to the lack of collection of bottom sediment samples from the dams. Riparian vegetation can reduce flow velocity and thus increases the settlement of microplastics in the water column (Wu et al. 2020). Moreover, riparian or aquatic vegetation helps to capture suspended particles from the water and hold sediments by the roots (Mudd et al. 2010), which also reduce the mobility of microplastics.

Modelling Studies

Due to the limitation of sampling and detection methods, the transport and distribution of microplastics in water cannot be estimated accurately, even if rational spatial and temporal variations of sampling are considered (Lebreton et al. 2017). The establishment of model estimating the long-distance transport of microplastics is important for predicting the inputs of microplastics generated inland to the marine environment (Siegfried et al. 2017). The horizontal transport of microplastics estimated by different models may be very different. For example, Mai et al. (2020) predicted global riverine plastic outflows from 2010 to 2050 using a robust model and obtained only one-fiftieth amount predicted by Jambeck et al. (2015).

Previous studies have simulated the release of microplastics in estuaries or along rivers and lakes using Lagrangian transport model over a long period of time. Using this model, Daily and Hoffman (2020) simulated the three-dimensional motion of three kinds of positive buoyant and six kinds of negative buoyant microplastics in Lake Erie induced by advection, density-driven sinking, and turbulent mixing, and illustrated the distribution of microplastics in the water and sediment. This model took into account the settling rate of microplastics with different densities, but ignored the density changes plastic caused by environmental conditions. In addition, the resuspension of microplastics was also ignored, so the abundance of microplastics deposited in the riverbed which was calculated by this model might be overestimated. Hoffman and Hittinger (2017) estimated the lakeside plastic input in the Laurentian Great Lakes, and calculated the transport and spatial distribution of microplastics in the Great Lakes from 2009 to 2014 using a hydrodynamic model. The results of the model were similar to those determined with the samples previously collected from Lakes Superior, Huron, and Erie. However, all the microplastics in this study were assumed to remain on the surface without considering the sinking induced by biofouling-driven density changes.

Besseling et al. (2017) parameterized the factors affecting the regression of microplastics by using the literature data, determined the attachment efficiency of heterogeneous aggregation using experiments, and calculated sediment retention distance required for 99% of the microplastics entering the water environment. However, this study was only designed for (near-) spherical microplastics, the effects of particle shape need to be evaluated before the model is applied to more diverging types of microplastics. Atwood et al. (2019) predicted the accumulation of spherical microplastics (with a diameter of 1 mm and a density of 0.91 g/mL) by river discharge on the adjacent coast using remote sensing model. The model was validated based on samples from nine beaches and found that remote sensing simulation can accurately predict the accumulation of microplastics in estuaries. The accumulation patterns were consistent with those of hydrodynamic simulation, suggesting that his method provides a foundation for the development of an operational monitoring system to assess microplastic pollution from a major river discharge.

Conclusions and Perspectives

The input of terrestrial origin microplastics via inland water systems are a main source of marine microplastic pollution. The understanding of aggregation, settlement, and transport of microplastics in inland waters will help to estimate the transport of microplastics in the whole water environment. The homogeneous aggregation of microplastics is mainly influenced by particle size, surface modification, aging degree of microplastics, metal ions, pH, surfactant, natural organic matter (NOM), etc. The colonization of organisms on microplastics are the priority among heterogeneous aggregation researches, influenced by properties of microplastics, organism species, and water conditions. Long-distance horizontal transport of microplastics in water is influenced by hydraulic conditions, rainfall, river morphologies, dams, vegetation, etc. Modelling studies can help to derive estimation of the transport and retention of microplastics over temporal and spatial scales that are impossible for observational studies.

Inland water systems include lakes and rivers. One of the most significant differences between rivers and lakes is hydrodynamic conditions. Compared to rivers, lakes have lower flow rates and longer water retention time, which allows much more deposition of microplastics. The lower flow rates and longer water retention time of lakes are also beneficial to the growth of organisms, especially microalgae, resulting in much more aggregation and settlement of microplastics (Hu et al. 2020). Due to some lakes being relatively closed systems and having long recycling times, most of the microplastics may be retained permanently, which still needs further investigation.

The following areas are suggested for future work:

(1) Laboratory simulations involving multiple factors require more attention. Future work should consider the use of aged and fouled polymer particles for a more complete and close-to-nature description of the behavior of microplastics in inland water environment (Kowalski et al. 2016).
(2) There is a lack of models that can be directly applied to the study of microplastics transport in rivers. The influence of the nature of microplastics on the transport needs to be parameterized in shape and size, which needs to be further simulated in the laboratory.
(3) The behavior of degradable plastics needs further study. In natural environments, the degradation time of some biodegradable plastics is still too long (Nazareth et al. 2019). The breakdown of the biodegradable plastics in the inland waters may hinder the understanding of the fate and transport of the microplastics in inland waters.
(4) The hydrologic conditions of freshwater are important information that aid in determining the transport and retention of microplastics. It is suggested that the hydrological characteristics of the sampling areas should be recorded. Finally, the comparison of microplastics fate and behavior in lakes and rivers require further investigation.

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