Available online at https://link.springer.com/journal/42241
http://www.jhydrodynamics.com
Journal of Hydrodynamics, 2023, 35(3): 379-395
https://doi.org/10.1007/s42241-023-0038-7

Longitudinal dispersive coefficient in channels with aquatic vegetation: A review

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(Received May 22, 2023, Revised June 26, 2023, Accepted June 27, 2023, Published online July 20, 2023)

Abstract: The determination of longitudinal dispersion coefficient in rivers is necessary for pollution control, environmental risk assessment, and management. In rivers with aquatic vegetation, the flow field is remarkably modified by canopies, which affects velocity profiles and dispersion characteristics dominated by the heterogeneity of the velocity field. The dispersion is deduced from lateral and vertical longitudinal velocity gradients for compound channels with vegetated floodplains and rectangular channels with river-wide vegetation, respectively. Although many efforts have been exerted to clarify the dispersion process in different conditions and predict the diffusion of contaminants in vegetated rivers, no studies have introduced it systematically. This study reviews the dispersion coefficient characteristics, including magnitude, main impacted factors, and relationships with flow and vegetation features, in channels with aquatic canopies considering the variation of impact factors changing with the different vegetation and river morphology scenarios. Several typical methodologies for determining longitudinal dispersion coefficients are also summarized to understand the dispersion processes and concepts. Apart from the pioneer outcomes of previous studies, the review also emphasizes the deficiency of existing studies and suggests possible future directions for improving the theory of dispersion in vegetated channels.

Key words: Vegetated flows, longitudinal dispersion coefficient, spatial heterogeneity

0. Introduction

Aquatic vegetation notably impacts the exchange and mixing processes of momentum, and the transport of solutes and particles in waterways, dramatically controlling the capacity of nutrients, suspended loads, and contaminants[1]. Previously, conventional river management practices involved removing aquatic canopies from open channels to mitigate their negative impact, such as increased obstruction and reduced flow capacity[2]. However, vegetation plays a crucial role in the improving water quality by absorbing nutrients and producing oxygen[3-4], and remarkably impacts mass transport in rivers[5]. In addition, aquatic vegetation is thought as an efficient measure against the flood damage as they provide shelter for fish during rapid discharge changes[6]. And the diversity of aquatic vegetation remarkably enhances fish diversity and abundance[7]. Both the negative and positive influences of canopies on the ecosystem and river management have prompted researchers to investigate the mechanisms underlying waterbody-vegetation interaction and substance transport, to improve the canopy management measures in natural rivers.

In recent decades, much work has shown in greater detail how vegetation alters flow velocity profile and turbulence features. One of the primary influences of canopies is the increase in flow resistance and subsequent reduction in conveyance capacity[8]. As a consequence of the drag forces, uniform vertical profiles of longitudinal velocity are generated in flows with emergent canopies, and the velocity magnitude depends on the vegetation density[9-10]. Vegetation constricts the evolution of largest eddy-scales, which contributes to turbulent diffusivity, on the range of stem diameter, d_v, to stems interval, Δs. Therefore, the turbulent diffusion is reduced by the decrease in both velocity and eddy scales in the emergent vegetated flows compared with the flow without canopies. On this basis, the turbulent diffusion coefficient, D_t, is usually related to velocity magnitude u_m and eddies scale l_e, i.e., $D_t \sim l_e u_m$ [11]. In channels with submerged canopies, the drag forces of vegetation are discontinuous in the vertical direction due to the presence of a strong shear region at the top

Projects supported by the National Natural Science Foundation of China (Grant Nos. 52020105006, 12272281).
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of canopies and thus dominate the hydrodynamic features of flow fields[12-14]. In accordance with the velocity and turbulence features, the flow field is usually divided into several layers, which can be found in the review of Nepf[10] in detail. Unlike the stem-scale eddies in flows with emergent canopies, there are two dominant turbulent eddy scales in flows with submerged canopies. The vegetation-scale turbulent eddies, also called Kelvin-Helmholtz (K-H) vortices, have been observed in the exchange region top of canopies and dominate turbulence intensity near the vegetation interface and vertical momentum/mass fluxes between the non-vegetated and vegetated regimes[15-16]. The turbulent intensity within the lower vegetation layer is primary controlled by stem-scale eddies behind stems[17-18]. The turbulent diffusion coefficient is also thought to have several layers resembling the velocity profile, and the largest turbulent diffusion is observed near the top of canopies and fluctuates with the instability of K-H vortex[19-20].

The change of flow field induced by the presence of aquatic vegetation affects mass transport in natural rivers, which is important for fluvial engineering, such as the management and assessment of pollutants and sediment deposition[21]. In ecological engineering, therefore, vegetation has been a central part of nature-friendly solutions used in multifunctional river management[22]. However, an improved understanding of the underlying transport and mixing processes is necessary to optimize their performance[23]. For the purpose, one of the most typical research topic in 1-D (along the streamwise direction) analytical models of water quality is the longitudinal dispersion coefficient, which is mainly caused by the spatial heterogeneous profile of longitudinal velocity[24]. For integrity and logicality, we first introduce the definition, concept and application of longitudinal dispersion coefficient in detail.

As shown in Fig. 1(a), in ideal stagnant water, the flux of scalar q can be obtained from Fick's law: $q_i = -D_m(\partial c / \partial x_i)$, where c is the scalar concentration, x_i is the coordinate axis in x_i direction, with $i = 1$, 2 and 3 representing x, y and z directions, respectively. D_m represents the molecular diffusion coefficient induced by Brownian movement, which is influenced by temperature, pressure, and mass characteristics. However, the scalar transport is controlled by both Brownian movement and velocity in the current. As turbulence is the most common in natural flow fields, the instantaneous velocity changes tremendously, leading to the variation of scalar concentration. This indicates that solutes are dispersed over the whole width of the stream, with some solutes cloud moving fast as relative large velocity and other moving slower as slower velocity[25]. Therefore, the velocity of streams plays a vital role in controlling the diffusion of pollution and also scalar concentration. Figure 1(b) shows one method to describe the effects of instantaneous velocity of turbulence on scalar mass transport, where the turbulent diffusion coefficient D_t and time-averaged velocity $\bar{u}$ are introduced to the Reynolds time-averaged advection-diffusion equation of scalar transport, and the mass flux is given by

$$q_i = \bar{u}_i c - D_m \frac{\partial c}{\partial x_i} - D_{t\_i} \frac{\partial c}{\partial x_i} \tag{1}$$

where D_{t_i} represents the turbulent diffusion coefficient in the x_i direction and varies in different positions and directions. The advection and turbulent diffusion terms are the main processes of scalar transport, and the molecular diffusion term is usually ignored in Fig. 1. However, the 1-D (along the x direction) or 2-D predictable models of mass transports must consider the dispersion term when time-averaged velocities at different positions are replaced by the area- or depth-averaged velocities in 1-D, 2-D models, respectively, due to the strong spatial heterogeneous of flow field induced by the multiscale turbulence vortexes. As shown in Fig. 1, taking the 1-D model as an example, the x_i direction mass flux can be derived using the following formula

$$q_x = \bar{U}_A c - (D_{t\_x} + k_x) \frac{\partial c}{\partial x} \tag{2}$$

where k_x is the longitudinal dispersion coefficient used to characterize the scalar transport induced by the heterogeneity of longitudinal velocity, $\bar{U}_A$ is the cross-sectional averaged longitudinal velocity.

Turbulent diffusion and dispersion are totally different, and the objective of the present review is to clarify the characteristics of dispersion by summarizing and discussing existing studies. Both turbulent diffusion coefficient and dispersion coefficient are typical characteristic parameters used to represent the effects of temporal or spatial fluctuations of flow fields on mass transport. Turbulent diffusion describes the effects of the temporal fluctuation of velocity on scalar diffusion and is closely related to flow conditions, such as laminar and turbulent flow, and the hydrodynamic structure of turbulence. The dispersion coefficient is a virtual parameter used to represent the variation between the temporal-spatial averaged velocity and the local time-averaged velocity, which compensates for the inaccuracy of results induced by the variations in 1-D or 2-D models, where the heterogeneous velocity flow is represented by a simplified spatial-averaged velocity.

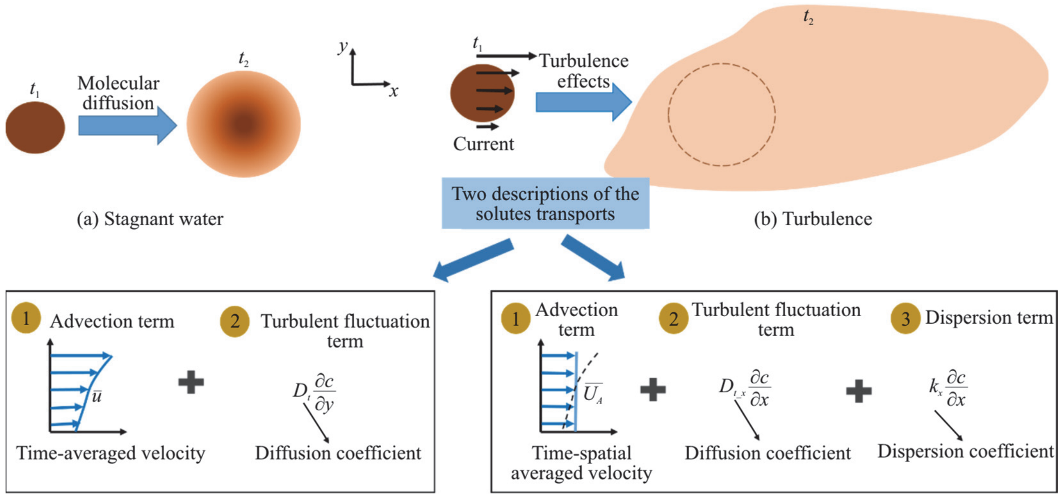

Fig. 1 (Color online) Diagram of scalar transport in different flow fields

In practice, the longitudinal turbulent diffusion is usually ignored in the 1-D model because its magnitude is much smaller than the longitudinal velocity[19]. The longitudinal dispersion process is described in the advection-dispersion equation, which is typically given as

$$\frac{\partial c}{\partial t}=\frac{\partial}{\partial x}\left(k_x\frac{\partial c}{\partial x}\right)-\bar{U}\frac{\partial c}{\partial x} \tag{3}$$

where t is the time, $\bar{U}$ represents the generalized cross-sectional averaged velocity, which can be the depth- or area-averaged longitudinal velocities.

Taylor[26-27] first developed dispersion theory in pipe flows and then the longitudinal dispersion coefficient of the open channel turbulent flow was first derived by Elder[28] through Reynolds analogy and the velocity profiles obtained in experiments. The theory was applied to natural rivers by Fischer[29], who proposed the triple integral expression of the longitudinal dispersion coefficient

$$k_x=-\frac{1}{A}\int_0^B hu'\int_0^y\frac{1}{\varepsilon h}\int_0^y hu'\mathrm{d}y\mathrm{d}y\mathrm{d}y \tag{4}$$

where A and B are the cross-sectional area and river width, respectively, h is the local flow depth, u' is the variation between the local velocity and area-averaged velocity, y is the coordinate in the lateral direction, ε is the local turbulent mixing coefficient. The formula indicates that k_x is highly sensitive to hydraulics, hydrology, and river morphology. The longitudinal dispersion coefficient can be determined quantitatively based on Equation (4) once the velocity profile and the cross-section geometry are provided. Many studies have tried to give the expression of k_x through different assumptions for lateral velocity profiles, such as logarithmic[30], power-law velocity profiles[31], and empirical velocity profiles[32].

As Fischer[29] indicated that only the transversal velocity variations are taken into account for the longitudinal dispersion coefficient in natural open channels while ignoring the vertical velocity variations cause the large ratio of width to depth, nearly overtaking 72, in common natural rivers. Apart from hydraulic and geometric conditions, ecological factors, such as aquatic vegetation, should be considered, especially in scenarios with aquatic canopies near the riverbank or floodplains. For these conditions, not only lateral profile of velocity should be taken into account, but also the vertical variations of the longitudinal velocity are important. Therefore, the dispersion changes remarkably with the presence of vegetation due to the changes in drag forces, flow velocity, and turbulence structures, which will be introduced in the next section.

Aquatic canopies introduce two main mechanisms that contribute to dispersion when contaminants pass through such regions, thereby distinguishing the dispersion process in flows with vegetation from those without. The first mechanism is similar to dispersion in no-vegetation channel flows, where the different movement velocity of concentration cloud induced by the velocity variation leads to distance variation between tracer particles 1, 3, that is represented by Δx_1 in Fig. 2. However, the obstruction of vegetation changes the route of particles and leads to longitudinal separation of particles, that is, dispersion[33]. The second mechanism is termed vortex trapping, which occurs behind canopy stems where the longitudinal velocity is relatively low or even zero, creating dead zones shown as gray regions in Fig. 2. The particles or solutes passing through vegetated regions are trapped in the recirculation region, and are re-released after the residence time. As a result, the vortex trapping leads to dispersion of the concentration cloud, represented by trajectory variations Δx_2, Δx_3. White and Nepf[34] theoretically derived an expression for the second dispersion coefficient in terms of the residence time and scale of the dead zone. The steady recirculation zone is necessary for the second dispersion mechanism and is satisfied when the Reynolds number is relatively small. By contrast, for large Reynolds numbers, the vortices are likely to shed from the dowel in a regular pattern, that is, vortex streets, and the solute trapped in the dead zone is periodically shed into the larger wake with the vortices[35]. This phenomenon weakens but does not eliminate vortex-trapping dispersion.

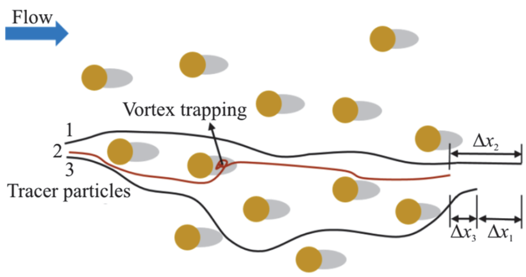

Fig. 2 (Color online) Schematic of two dispersion mechanisms in the flow with the vegetation array

The two abovementioned dispersion mechanisms are particularly important in flows with emergent canopies. However, in flows with submerged canopies, the effect of mixing vortexes between the vegetated region and overflow is stronger and more important than the effect of trapping vortexes behind stems. Therefore, most studies have focused on analyzing the impact factors of dispersion, such as vegetation density[36], submergence[37] and profiles[38], depending on the analysis of velocity variations. However, the large Reynolds number and complex canopy structure in natural rivers makes it difficult to predict the velocity variations accurately. For example, the velocities in the vegetated regions are constricted by the drag force of canopies, leading to the regions with low or no flow, termed dead zones, which remarkably increases the resistance time of fine particles and contaminants in the river, floodplains, and wetlands[39]. Considering that the flexible plants in natural rivers are more common and grow in community patterns [40], many studies have focused on the dispersion coefficient with plant clumps or flexible canopies[41-42]. However, these studies all need to deal with the bottleneck that is how to describe and quantify the vegetated arrangement and flexibility. Park and Hwang[43] used the ecological concept of standardized Morisita index I_p to qualify the vegetation heterogeneity with isometric and allometric arrangements, and concluded that the longitudinal dispersion coefficient is positively related to I_p, indicating that increased heterogeneity of plant clumps enhances the magnitude of k_x.

In summary, the presence of aquatic vegetation remarkably affects the dispersion mechanisms and processes, and the magnitude of the longitudinal dispersion coefficient is controlled by multiple impact factors. The objective of this review is to comprehensively introduce the effects of aquatic vegetation on the longitudinal dispersion coefficient, emphasize the difficulties and opportunities of current research, and propose possible prospects for solving corresponding problems in the future.

1. Longitudinal dispersion induced by vertical heterogeneity

According to the concept of the dispersion, the magnitude of longitudinal dispersion is dependent on the spatial heterogeneity of flow fields, including both transversal and vertical directions. Efficiently simplifying the determination of k_x requires considering the main effects based on the relative intensity of unevenness in these directions. This review aims to introduce the features of dispersion induced by vertical and lateral heterogeneity to clarify the mechanisms of dispersion in different scenarios.

This section discusses conditions where river-wide vegetation covers the riverbed, making lateral differences in velocity negligible. Dispersion induced by vertical variations in velocity is mainly generated by three typical vegetation morphologies, that is, emergent, submerged, and suspended vegetation. In these flows, the longitudinal velocity strongly adjusts along the vertical direction, as shown in Fig. 3. The velocity profile is significantly important for the analysis of the longitudinal dispersion coefficient, and the main factors affecting k_x change remarkably with different vegetation conditions.

1.1 *Emergent vegetation*

For channels with emergent canopies, the vertical profile of longitudinal velocity is uniform (Fig. 3(a)), and the barrier of vegetation reduces the integral flow velocity, which leads to smaller longitudinal dispersion than that in open channel flows without canopies[36]. Studies focusing on dispersion in channels with emergent canopies commonly preferred to explore the impact factors and relative intensity of two dispersive mechanisms, that is, dispersion induced by vortex trapping behind stems and the spatial heterogeneous velocity field, k_v, k_s [34]. In general, the main impact factors include canopy density and diameter of canopy stems in accordance with existing studies

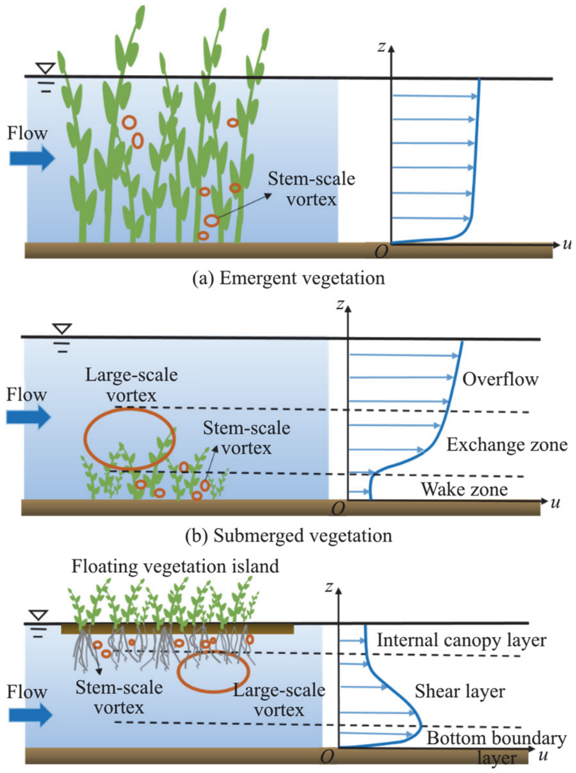

Fig. 3 (Color online) Diagram of three types of vegetation in rivers and their corresponding velocity profiles

The variation of the heterogeneous velocity field created by the randomly distributed perturbations of velocity behind each stems is directly related to the stems array density. The increase in vegetation density generates more vortex-trapping regions, i.e., larger k_v, but constricts the turbulent intensity and Reynolds number which constrains the shedding of wake vortexes, i.e., larger k_v [34]. It indicates that the vortex-trapping dispersion is positively related to the vegetation density. At the same time, the shear dispersion of spatially heterogeneous velocity closely depends on the magnitude of velocity, which is hugely reduced by the increasing vegetation density, leading to smaller k_s. Obviously, the two inversely related effects of vegetation density contribute to the complex variation of dispersion with stem density. According to the limiting-experiment measurements of Nepf et al.[33], the effect of turbulence intensity is overshadowed by the effect produced by an increase in vegetation density, and thus the longitudinal dispersion coefficient decreased with the increase in vegetation density. The study also monitored diminished dispersion within the regions of high plant density as compared to the regions of open water within coastal estuaries[44]. However, the experimental study of White and Nepf[34] subsequently concluded that the two opposite effects offset each other, and as a result, the dispersion is only weakly dependent on canopy density, especially for the scenario with a sufficiently high Reynolds number. These findings indicated that the Reynolds number is also crucial to describing the mechanism of dispersion when analyzing the effect of vegetation density. However, several important questions remain unanswered because existing studies have focused on specific and limited Reynolds number. For example, what Reynolds number represents the threshold at which vegetation density becomes the dominant factor in dispersion remains unclear, how the two inverse effects of vegetation density on dispersion change with the Reynolds number, and under what conditions the vortex-trapping dispersion coefficient k_v can be ignored compared with the spatial heterogeneous dispersion k_s, and vice versa.

As the length scale of turbulent vortexes is closely related to the size of stems in arrays, some studies also investigated the relationship between vegetation diameter and the longitudinal dispersion coefficient, which varies significantly with aquatic vegetation biomass and dispersion characteristics through the seasons. For example, the change in stem size of *Typha* with the season affects dispersion by causing stem clusters to act as a single, larger obstacle or by trapping flow within the clusters[45]. The results showed that the dispersion coefficient and the stem diameter is positively related according to the dispersion features in flows with two species (*Carex acutiformis*, *Typha latifolia*) in two seasons (winter, summer), and the observed stem diameter is utilized to highlight the sensitivity of common dispersion model to the key length-scale descriptor[46]. However, another length scale, the interval of stems, is also important. Sonnenwald et al.[47] proposed using stems spacing as the appropriate length-scale normalization for k_x in vegetated flows rather than diameter of stems. In conclusion, the nondimensional longitudinal dispersion coefficient by the characteristic length-scale of turbulent eddies, whether stem diameter or spacing interval, is a representative and useful method to incorporate spatial heterogeneity. However, existing expressions of k_x derived from the stem diameter and spacing interval are both single length scale, and in flow fields with canopies, multiple length-scale eddies are common. Thus, confusion still exists on how to specify the dispersion coefficient based on multiple length-scale vortexes. Additional studies are needed to explore how vegetation is described in expression of the longitudinal dispersion coefficient in flows with complex vegetation arrangements, such as different stem diameters or spacing intervals.

1.2 *Submerged vegetation*

In channels with submerged vegetation, the longitudinal dispersion coefficient increases sharply relative to emergent conditions because the multi-layer flow structure increases the vertical velocity gradient[48-49]. As shown in Fig. 3(b), the flow can be generally divided into three layers in the vertical direction based on the velocity magnitude and gradient. Specifically, the large-scale vortex exists in the exchange region, which promotes mass and momentum exchange between vegetated and non-vegetated regions. In flow fields with submerged vegetation, the three contributing processes to solute transport include large-scale shear dispersion above the canopy, velocity variations between canopy and overflow, and the stem-scale dispersion within the canopy[50]. The submergence ratio of the canopy, i.e., the ratio of water depth to vegetation height $(S_r = H / h_v)$, significantly affects the length scale of coherent vortices at the exchange region between canopies and overflows, and thus is expected to dominate the shear dispersion and exchange intensity, and the production of stem-scale vortexes. Therefore, the impact factor, submergence ratio, has been investigated extensively in the last few decades[51-52].

For small S_r value, the exchange between canopies and the overflow dominates the total dispersion, and k_x increases with an increase in S_r because large-scale shear dispersion is enhanced and eventually dominates vertical mass transport[53]. Limited existing studies show that a positive relationship exists between submergence ratio and dispersion ranging from 1.0 to 3.5[37, 54-55]. For the large S_r value, that is, deeply submerged canopies $S_r > 10$, although the canopy-scale vortices interact with larger boundary-layer turbulence, stretching the canopy-scale vortices and enhancing secondary instabilities[56-57], the vertical gradient of longitudinal velocity declines as the proportion of the overflow increases. It indicates that k_x is likely to decrease with the increase in submergence ratio as the velocity approaches to logarithmic boundary layer in open channels with rough riverbeds, i.e., canopies. The study of Huang et al.[51] found that the longitudinal dispersion coefficient is reduced in deep water (large submergence ratio) and enhanced in shallow water (small submergence ratio). Although their results are based on the effect of canopies and tidal flows, the generalized characteristics of dispersion in the flow with deeply submerged vegetation are exhibited to a certain extent. From a practical perspective, clarifying the relationship between submergence ratio and dispersion based on the studies on small and moderate S_r conditions is sufficient.

Furthermore, the canopy density cannot be ignored when discussing dispersion because it directly affects the penetration length and the stratification characteristics of the velocity. Nepf et al.[58] stated that, in accordance with the retention time within canopy regions, the coherent vortexes penetrate far into the canopy, and water renewal occurs over time scales of minutes to tens of minutes when the canopy density is small. By contrast, the penetrated length is much smaller than the vegetation height, and the vertical mass transport is controlled by stem-scale turbulence vortexes when the canopy density is large. Thus, the timescale is much longer, on the order of hours. The longer retention time usually implies a larger k_x. Despite the study by Shin et al.[37] showing that the concentration-based dispersion and velocity-based dispersion are slightly different from each other, and that the level of dispersion only deduced from retention times is insufficient, they also found that an increase in canopy density increases the longitudinal dispersion coefficient and the variation of velocity between the overflow and the canopy-region slow current.

1.3 *Suspended vegetation*

Constructing floating treatment islands, such as floating vegetation islands, is one of the most cost-effective and eco-friendly solutions to absorb pollution, as well as beautify the urban landscape[59]. Therefore, aquatic canopies existing as suspended vegetation in urban rivers are common. As shown in Fig. 3(c), the submerged and suspended canopy flows have many similar properties, such as the reduced velocity within the canopy region, distinguishable two-layer flows (rapid and slow current regions), and the large scale K-H vortexes near the interface of canopy regions and the non-vegetation region[60-61]. The main difference between the two types of flows is the influence of the bottom boundary layer beneath the canopy for the flow with suspended canopies and the exerted drag force at the water surface rather than free surface in the channel with submerged canopies[62]. The dispersion characteristics in the river with suspended vegetation change remarkably due to this difference.

As shown in Fig. 3(c), the velocity increases above the bottom boundary and maximizes at a point between the canopies and riverbed, then decreases into and within the canopies. The maximum Reynolds shear stresses are observed at the interface of canopies and the current and the minimum at the velocity maximum point, implying strong shear dispersion at the shear layer near the interface[63]. They also emphasized that the longitudinal dispersion coefficient can be effectively predicted by a three-zone model once the velocity profile and key points, i.e., maximum velocity point, are known. Liu et al.[64] conducted random displacement model to numerically simulate the longitudinal dispersion coefficient in the channel with suspended canopies, and concluded that the suspended vegetation can increase Fickian time, that is, it will take longer time for the longitudinal dispersion coefficient to reach stability. Ai et al.[65-66] investigated the dispersion process by analyzing the concentration cloud distortion, the temporal evolutions of dispersion intensity, and the displacement of the cloud centroid at the preasymptotic stage. Their study stated that the initial condition dominates the behavior of concentration cloud. These studies help to clarify the dispersion processes in the suspended vegetated channels from different aspects.

2. Longitudinal dispersion induced by transverse heterogeneity

In this part, we focus on laterally heterogeneous vegetated flows, where aquatic canopies do not create effective vertical velocity gradients, and remarkable transversal velocity gradients are observed and impact the longitudinal dispersion coefficient of channels. In natural rivers, the shape of cross section is irregular, as shown in Fig. 4. Considering the effects of vegetation on longitudinal dispersion is important when the riparian transects are flooded for large discharges of rivers as the vegetation is commonly observed in both natural and rehabilitated floodplains. The vegetation and floodplain enhance the velocity difference between main channels and floodplains, and thus boost the lateral heterogeneity of velocity profiles and the longitudinal dispersion coefficient. The results showed that the typical non-uniformity of the vegetation biomass plays a key role in transversal velocity gradients[67]. In a word, it is crucial to analyze the impacts of floodplains and near-bank vegetation on the longitudinal dispersion coefficient.

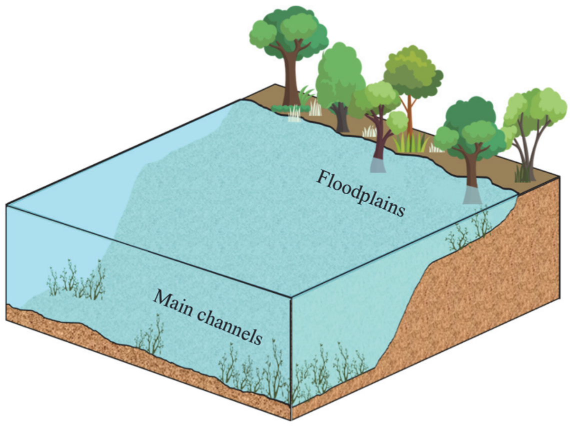

Fig. 4 (Color online) Diagram of the generalized hydraulic environment of rivers and vegetated floodplains

Several typical cross-sectional morphologies with aquatic canopies are shown in Fig. 5, illustrating the crucial factors that influence dispersion in different cross sections and vegetation patterns. Compared with rectangular open channels, the preseof riparian vegetation and floodplains significantly reduces longitudinal flow velocity within vegetated regions. Thus, channels with floodplains and riparian

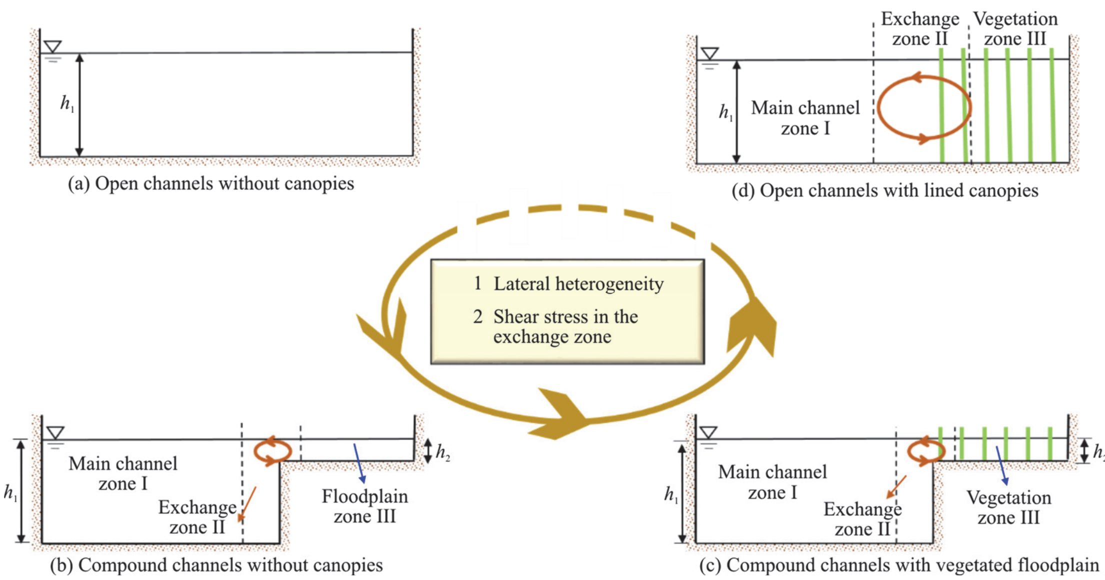

Fig. 5 (Color online) Diagram of the dispersion induced by the transverse heterogeneity of velocity

vegetation exhibit a rapid-flow zone (the main channel region) and a slow-flow zone (the floodplain region). The strong shear stresses induced by the velocity gradients near the interface, that is, exchange regions, greatly contribute to the intensity of coherent vortexes. In channels transitioning from the rectangular to compound channel morphology, that is, Figs. 5(a), 5(b), the velocity within the floodplain zones is smaller than that in the main channels, and the secondary currents and coherent vortexes occur within the exchange zone induced by the enhanced shear stress[68]. This explains the general phenomenon that the longitudinal dispersion coefficient in compound channels is larger than that in rectangular open channels[69].

For vegetated floodplains, i.e., Fig. 5(c), the drag forces exerted on the current by the vegetation constrict the velocity within the floodplain zone, resulting in an increased difference of streamwise velocity between the floodplains and main channels and generating a high-shear layer at the interface[70]. At the same time, the emergent canopies in floodplains suppress the momentum exchanges between the two regions[71], indicating that the scale of coherent vortexes is constricted by canopies. Therefore, the effects of vegetated floodplains on the dispersion coefficient are influenced by multiple factors, which will be discussed in detail in the following paragraphs (Sections 2.1, 2.2). The current consensus is that pollutants takes a longer time to spread in compound channels with vegetated floodplains[72-74], indicating that the absolute maximum velocity in both the main channel and floodplain decreases with the presence of vegetation in floodplains, resulting in smaller dispersion. The study of Sun and Shiono[75] also supports these conclusions, as velocity, flow discharges and boundary shear stress were remarkably reduced in vegetated compound channels compared with those in non-vegetated conditions. However, the longitudinal dispersion coefficient in compound channels with vegetated floodplains is usually larger than that in bare compound channels. As discussed above, the lateral profile of longitudinal depth mean velocity expresses more variations, that is, larger transversal spatial heterogeneity. Channel scale variations in velocity dominate the longitudinal dispersion coefficient rather than the decrease in velocity magnitude. Therefore, k_x in vegetated compound channels is larger than that in smooth compound channels.

Figure 5(d) illustrates a generalized depth-mean velocity profile along cross sections. In channels partially covered by emergent vegetation near the riverbank, the velocity profile exhibits a distinct two-zone structure consisting of a main channel and a rapidly varying shear layer across the vegetation interface[76]. This structure contributes remarkably to the magnitude of the longitudinal dispersion coefficient. Depending on experiments and N-zones model, Huai et al.[74] found that the non-uniform depth-averaged longitudinal velocity profiles within vegetation regions caused extra longitudinal dispersion, which is usually ignored in studies and potentially leads to underestimated k_x [77]. They also indicated that the velocity profiles in the main channels are totally different from those in flumes without vegetation. Therefore, the formulas used to estimate the mean velocity and the longitudinal dispersion coefficient should be carefully improved, or the N-zone model will yield results with large errors.

2.1 *Influence of depth ratio on the longitudinal dispersion coefficient*

Vegetation characteristics and relative depth, defined as the ratio of the floodplain flow depth (h_2) to flow depth in the main channels (h_1), i.e., $D_r = h_2 / h_1$, are the main factors affecting flow dynamics in vegetated floodplains. The objective of this review is to compare and analyze the results of existing studies on these factors and their influence on the longitudinal dispersion coefficient.

In the section, we focus on discussing the relationship between the longitudinal dispersion coefficient and relative depth, as it is the main variable factor in natural rivers during different flood dates. As Fig. 6 shown, increasing water depth leads to an increase in D_r and flow area, thereby enhancing the discharge capacity. However, the exchange intensity between two regions is constrained by the vegetation density and flow depth of floodplains[76]. The change in the longitudinal dispersion coefficient with D_r is still controversial due to multiple impact factors.

Before discussing the response of the longitudinal dispersion coefficient to the depth ratio of floodplains to the main channels, the hydraulic features of the compound channel flows with varying D_r should be briefly explained. Different water depths, which are the main variables for different relative depth in natural rivers, affect the discharge capacity, variations in velocity, and momentum exchange between the main channels and floodplains, characterized by secondary currents and coherent vortexes[78-80]. Many studies have investigated the momentum exchange between the main channels and floodplains based on the shear stress near the interface[81] or the scale of coherent vortexes[82]. Some studies found that the scale of coherent vortexes and the mean velocity are both enhanced by the increase in the relative depth, leading to stronger momentum exchange. Some studies also showed that the flow discharge was slightly reduced by the increase in D_r,

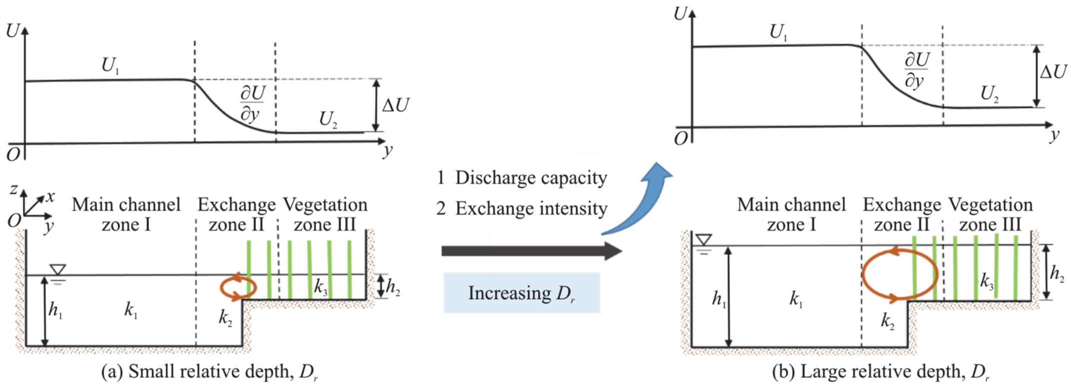

Fig. 6 (Color online) Schematic diagram of the effect of D_r on the longitudinal dispersion in compound channels with vegetated floodplains

leading to a decrease in mean velocity of cross sections[75]. The different hydrodynamic response of the channel mean velocity and coherent vortexes to the variation of the relative depth may explain the uncertain change of the longitudinal dispersion coefficient, which will be discussed in detail in the following sections.

In accordance with the experimental results of Hamidifar et al.[72], the delay time induced by the vegetated floodplains decreases with the increase in D_r. The fact that the depth ratio weakens the impact of vegetation on the main channel flows and increases the velocity magnitude in the main channels may account for the negative correlation between the delay time and the relative depth. Specifically, both the velocity in main channels and floodplains increase with the increase in the relative depth, generating a larger k_x, which is supported by several available studies[72-73, 83]. In addition, the effects of canopies on the change of velocity in the main channel increase with the increase of D_r, resulting in a larger incremental rate of k_x compared with the compound channels without vegetation, where the lateral velocity variations are reduced by large relative depth. Interestingly, in accordance with the recent experimental study of Ref. [84], the longitudinal dispersion coefficient is reduced by the increase in the relative depth in the compound channels with vegetated floodplains, although the dispersion in the vegetated compound channels is also larger than that in the bare compound channels. The controversial results may be ascribed to the fact that the mean cross-sectional velocity in the study of Gu et al.[84] decreased with the increase in D_r, whereas the increase in the depth ratio leaded to the raise of mean velocity in other studies[72, 83]. These results imply that the magnitude of mean velocity dominates the characteristics of dispersion within many influential factors, and has a positive relationship with the longitudinal dispersion coefficient. However, the specific reaction of velocity in the main channel and floodplains to the depth ratio is still unclear. More studies should be conducted to clarify the relationship between velocity magnitude and the depth ratio. The exchange intensity, representing the velocity gradient in the interface of the two zones, is also important for the dispersion coefficient, but the analysis about the factor is lacking in existing studies.

2.2 *Influence of vegetation characteristics on the longitudinal dispersion coefficient*

The micro-scale changes in flow fields induced by canopy characteristics, such as density and arrangements, are negligible compared with the macro-scale 1-D model of mass transport in rivers. Therefore, few studies have focused on the effects of vegetation characteristics on the longitudinal dispersion coefficient. However, the dispersion coefficient is efficiently used to compensate for the deficiencies of 1-D transport models, where the spatial variations of flow fields are usually ignored. Investigating the relationship between vegetation characteristics and the longitudinal dispersion coefficient benefits the knowledge of the interaction mechanism of vegetation and mass transport, and is meaningful for environmental management and assessments. This section introduces the main results of existing studies on the effects of vegetation characteristics.

Researchers have studied the influence of vegetation density on the longitudinal dispersion coefficient using experimental and theoretical methods. Vegetation occurring along river floodplains deeply alters the hydrodynamic flow structure, inducing a characteristic shear layer profile and triggering the onset of large-scale vortices, which promotes spatial dispersion[85]. In the system, the vegetation density plays an important role in regulating the velocity difference because thee extended drag force of aquatic vegetation reduces the flow velocity, which increases with the growth of vegetation density. The resistance coefficient of compound channels increased with the increase in vegetation density, whereas the bulk drag coefficient usually decreases as the vegetation density increases, due to the impact of wakes forming behind the vegetation[86]. Considering these multiple influences of vegetation density, the experimental results of Gu et al.[84] illustrated that k_x had a positive correlation with vegetation density: The longitudinal coefficient remarkably increased with the increase in vegetation density when the canopy density was small, and k_x slightly raised for relatively large vegetation density. The strengthened shear stresses change the transversal profile of the longitudinal velocity, which influences exceed the effect of the reduction of cross-section velocity induced by the increase of drag forces, thereby promoting the dispersion of flows.

The change of k_x with different vegetation arrangements, including the regular/irregular arrangements of canopies and the patterns of vegetation communities, has also caught researchers' attentions in recent years. Comparing the residence time in the compound channels with random and tandem arrangement of vegetation in floodplains found that vegetation with tandem arrangement elongates the delay time of the tracer dye, whereas the measurements of the longitudinal dispersion coefficient showed minor differences for conditions with regular and irregular arrangements[87]. However, from the aspect of flow fields, some typical studies showed that irregular arrangement of canopies play an important role in the spatial heterogeneity and thus dispersion[34, 88]. Huai et al.[89-90] also conducted a series of studies to explore the relationship between vegetation characteristics and spatial dispersion, and concluded that a more remarkable increase in dispersion induced by the change of vegetation structure than that induced by the variation of the turbulent intensity represented by the Reynolds number. It is worth noting that the inadequate agreements may be generated by the direct implementation of the dispersion coefficient obtained in the microscale to the macroscale 1-D mass model, which is a common usage of the longitudinal dispersion coefficient in engineering. Therefore, whether the intrinsic vegetation structure impacts the longitudinal dispersion coefficient is still unclear, given the limited and controversial outcomes.

In recent years, studies on the effects of vegetation patch patterns on the longitudinal dispersion coefficient have mainly focused on the coverage and the location of patches. The predictor of Perucca et al.[73] indicated that low-coverage patches can lead to a maximum of three times larger impact on reach-scale dispersion than homogeneous vegetation on floodplains, which can increase k_x of compound channels by 1.5-fold. Dang et al.[91], Vastila et al.[41] both illustrated a positive relationship between k_x and the coverage of vegetation patches based on numerical and experimental results, respectively. To some extent, the increase in the vegetation coverage indicates a higher canopy density, and the relationship between dispersion and vegetation density can be predicted. When considering the scenario with vegetation patches in the compound channels, the location of patches compared with the fully covered vegetation is also a crucial factor. Patches located in low-velocity areas, such as near the river bank, usually generate larger dispersion and longer residence time[41]. This phenomenon may be due to the fact that vegetated regions and the areas between longitudinally subsequent wake flows contribute to the dispersion process. Combining the results of Ref. [39], sparse or low-coverage canopies situated in the center of cross sections enhance velocities close to banks, and bank-side patchy vegetation accentuates the cross-sectional velocity variability, thereby increasing the dispersion intensity. It could be preliminarily inferred that the shear stresses of velocity along the transversal direction are the main mechanism contributing to higher k_x in channels with vegetation patches.

3. Influences of vegetation patches

When vegetated patches grow in channels, they create stem-scale vortexes and patch-scale vortexes that impact dispersion[92]. The highest dispersive fractions of vegetated patches are typically larger than those of randomly distribution stems[41, 93]. Two problems have drawn the attention of researchers. The first topic is the effect of the arrangement and diameter of the patch on dispersion. The results show that the longitudinal dispersion coefficient increases with the diameter of stems in channels with scattered vegetation stems[34, 42]. However, in channels with vegetated patches, the stem-diameter length scale is not the typical scale for dispersion, because the patch-scale vortexes dominate mass mixing five times higher than stem-scale vortexes[43]. As a result, the effect of the increase in the length scale of the patches arrangement exceeds the effect of the drag force of stems. Although existing studies have explored the topic of patch scale, much more works are needed to understand the dispersion mechanisms of vegetated patches in the future.

The second topic of concern regarding the vegetated patches is their coverage and density. Park and Hwang[43] used the standardized Morisita index I_p to express the heterogeneity of clump arrangements.

However, the study of Vastila[41] showed that I_p had noticeably poorer predictive power than that observed in the sparse vegetated patches condition of Park and Hwang[43], with 1-3 orders magnitude lower value. The results indicated that both patch density and location control dispersion. Considering that experimental studies on canopy patches is expensive and time consuming, numerical investigations are used to study the effects of vegetation patch coverage rather than experiments. Overall, although the hydrodynamic mechanism of patchy vegetation and longitudinal dispersion is unclear, the numerical results show that k_x gradually increases with the growth of vegetation coverage and tends to stabilize when a stable vegetation landscape is reached[91, 94].

In summary, the study on the effects of vegetated patches on the longitudinal dispersion coefficient is still in its initial development stage, limited by the valid description approach of patch features, such as arrangements and patch shapes. The longitudinal velocity changes along lateral and vertical directions, and varies along the longitudinal direction, making it difficult to derive the longitudinal dispersion coefficient mathematically. However, most aquatic vegetation grows in natural rivers with the form of patches. Therefore, enhancing our understanding of the mixing and dispersion processes can benefit river managements and assessments. To convenience, Table 1 lists the highlights for mainly existing studies on the longitudinal dispersion coefficient in channels with vegetation.

4. Determination methods of the longitudinal dispersion coefficient

Three methodologies, namely, the routing method, moment method, and integral method, are commonly used to derive the longitudinal dispersion coefficient. Here, we introduce these typical approaches and discuss their shortcomings/advantages.

4.1 *Routing method*

The routing method optimizes the longitudinal dispersion coefficient by comparing the predicted and measured concentration profiles and minimizing the errors between them. A routing solution for the 1-D advection-dispersion equation, varying in the time longitudinally, was proposed as follows[95-96]

$$c(x_2,t)=\int_{\tau=-\infty}^{\infty}\frac{c(x_1,t)u}{\sqrt{4\pi k_x\bar{t}}}\exp\left[-\frac{u^2(\bar{t}-t+\tau)}{4k_x\bar{t}}\right]\mathrm{d}\tau \tag{5}$$

where $c(x_1,t)$ and $c(x_2,t)$ are the upstream and downstream concentration profiles, $\bar{t}$ represents the travel time and τ is the integral variable. The downstream concentration profile can be predicted by Eq. (6) based on the given time, velocity, and assumptive k_x, and then the best-fitted k_x is determined by minimizing the sum of errors squared between the measured and predicted downstream concentration profiles[36, 46, 54, 97]. This method is the most commonly used for the experimental measurement of the longitudinal dispersion coefficient due to its high efficiency and wide applicability.

4.2 *Moment method*

The moment method determines k_x by analyzing the moment of concentration of the tracer. In this approach, the variation in the tracer cloud concentration escalates linearly over time, and the longitudinal dispersion coefficient is given by the following expression

$$k_x=\frac{U^2}{2}\left[\frac{\sigma_t^2(x_2)-\sigma_t^2(x_1)}{t_2-t_1}\right] \tag{6}$$

where U is the stream mean velocity, $\sigma_t^2(x_2)$ and $\sigma_t^2(x_1)$ are the variance of the tracer cloud concentration at downstream and upstream positions. In addition, the random displacement model is commonly adopted to simulate the longitudinal dispersion coefficient based on the change in the concentration moment. For numerical studies, the variations of tracer particles rather than the concentration cloud are calculated against the elapsed time[53, 64, 98].

In theory, the moment method is only valid within the diffusive period, that is, when no obvious dispersion or wake effects occur. Wake vortexes can generate retention of the tracer, leading to skewness of concentration clouds, consequently making it difficult to obtain a meaningful value of the variance[96]. In channels with canopies, the strong vortex-trapping effects in the wake layer of vegetated regions make it highly sensitive to the canopy features to define the start and end of tracers, which can impact the variance of distributions. To address this issue in channels with submerged canopies, Murphy et al.[53] refined the tracer profile through an optimization matrix to find the best-fitted value to the measured profiles utilizing a routing procedure. Further details of the optimization procedure can be found in Refs. [99-100]. However, the uncertainty of the start and end of concentration profiles still limits the application of the moment method.

4.3 *Integral method*

The integral method is an empirical and velocity-based methodology that analytically derives k_x by

Table 1 Summary of highlights in studies on the longitudinal dispersion coefficient

Vegetation patterns	Sources	Impact factors	Highlights
Emergent vegetation	Nepf et al.[33]	Vegetation density	k_x decreases with the increase in vegetation density
	White and Nepf[34]	Vegetation density	Vortex trapping dispersion k_v is positively related to vegetation density, but k_s is negatively related to vegetation density
	Sonnenwald et al.[46]	Stem diameter, d_v	k_x, d_v is positively related
	Sonnenwald et al.[47]	Stem intervals	Stem intervals are more appropriate to quantify k_x in vegetated flows than d_v
Submerged vegetation	Shin et al.[37], Shucksmith et al.[54] and Shucksmith et al.[55]	Submergence ratio, S_r	Positive relationship between S_r and dispersion when S_r ranges from 1.0 to 3.5
	Huang et al.[51]	Submergence ratio, S_r	Dispersion is negatively related to S_r when S_r overtakes 10
	Nepf et al.[58], Shin et al.[37]	Vegetation density	k_x increases with the vegetation density
Suspended vegetation	Liu et al.[64], Ai et al.[65, 66]	-	Analyzing the dispersion process: Concentration cloud distortion, the temporal evolutions of dispersion intensity, and the displacement of the cloud centroid at the preasymptotic stage
Compound channels with vegetated floodplains	Hamidifar et al.[72], Perucca et al.[73] and Farzadkhoo et al.[83]	The depth ratio of floodplain to main channel, D_r	The increase in D_r increases the dispersion, which may be explained by the increased velocity in both main channels and floodplains
	Gu et al.[84]	The depth ratio of floodplain to main channel, D_r	The increase in D_r decreases the dispersion, which may be explained by the decreased velocity in both main channels and floodplains
	Gu et al.[84]	Vegetation density	Positive relationship between vegetation density and dispersion
Vegetation patch	Park and Hwang[43]	Patch arrangements	Effects of the increase in the length scale of patch arrangements exceed the effects of the drag force of stems
	Dang et al.[91], Kalinowska et al.[104]	Patch density or coverage	k_x gradually increases with the growth of vegetation coverage and tends to stabilize when a stable vegetation landscape is reached

integrating equation (4) with given velocity profile and cross-sectional geometry, rather than using the above two concentration-based methods. The lateral and vertical profiles of the longitudinal velocity are vital to solve the complicated triple integration. Therefore, the problem of k_x is converted to the analytical longitudinal velocity profile in the vertical and transversal directions. In channels without canopies, which are relative easy. Many studies have focused on different assumptions for the longitudinal velocity profile to generate accurate estimation of the dispersion coefficient[31, 101]. However, in channels with aquatic canopies, the velocity changes based on hydraulic conditions, vegetation structures, arrangements and density. To simplify the problem, Chikwendu[102] proposed an N-zone model to predict the dispersion coefficient in a system with N distinct velocity zones over the vertical plane, and the generalized expression for k_x is shown as

$$k_x = \sum_{j=1}^{N-1} \frac{(\lambda_1 + \cdots + \lambda_j)^2 [1 - (\lambda_1 + \cdots + \lambda_j)]^2 \left[U_{1,j} - U_{(j+1),N}\right]^2}{b_{j(j+1)}} + \sum_{j=1}^{N} \lambda_1 k_{xj} \tag{7}$$

where $\lambda_j = h_j / H$, H and h_j are the water depth and the thickness of the j zone, U_j and k_{xj} are the cross-sectional mean velocity and the longitudinal dispersion coefficient in the j zone and $b_{j(j+1)}$ is the exchange coefficient between j and adjacent $j+1$ zones.

The application of the N-zone method to flows with canopies deals with the integration difficulty of complicated velocity profiles and the distinct velocity variations in vegetated and non-vegetated regions that cause vegetation drag forces. Murphy and Nepf[53] proposed a two-zone model to predict k_x, which represents three distinct processes that contribute to dispersion in channels with submerged vegetation. Shucksmith et al.[54] developed a two-zone model to calculate k_x in submerged vegetated flows and calibrated it with experimental data. Feasibility of the two-zone model depends on the penetration depth of the mixing layer, i.e., δ_e. When δ_e is larger than the vegetation height, the wake layer does not exist and two-zone model is suitable to describe the flow and express longitudinal dispersion with a summation of mixing caused by the velocity shear in the boundary layer plus contributions from wake-scale mixing within canopy region. When δ_e is small, no distinction between the mixing layer and the wake layer in the two-zone model. A complex profile of diffusivity over the flow depth is observed, and relatively high levels of mass transfer occurs at the interface. Hence, the two-zone model may be extremely simplistic to precisely describe the longitudinal dispersion. In brief, the accuracy of the N-zone model remarkably depends on the distinction of flow corresponding to the characteristics of velocity and mixing.

Integrating formulas three times can be difficult, and the natural variation of velocity and cross-sectional geometry in rivers can remarkably affect the derivation of k_x. This complexity is further complicated by the variety of river conditions. Therefore, although integration methods are mathematically and conceptually sound, they may require additional numerical approaches to simplify velocity expressions, such as the N-zone model and genetic programming (GP). Fang et al.[52] derived an analytical solution for the longitudinal velocity in submerged vegetated channels, simplified the expression of velocity, and then substituted the simplified expression into triple integration to calculate k_x. However, the difficulty of this method limits its application to more complicated flow fields, such as channels with vegetated patches.

4.4 *Other available numerical methods*

In addition to the routing and moment methods, which are both concentration-based methodologies, and the integral method, which is velocity-based methodology, there are also some available numerical methods, such as artificial neural network[103-104], GP[105], and machine learning algorithms[106]. These methods efficiently improve the methodology of the longitudinal dispersion coefficient, but their results depend heavily on abundant experimental data and may not be widely applied to specific problems.

5. Conclusion and research challenges

In accordance with the review of available studies, this review clarified the difference between turbulent diffusion and dispersion, and highlighted that the spatial heterogeneity of velocity is the crucial factor affecting dispersion features, which is impacted by the morphologies of channels, flowrates, and vegetation characteristics, such as profiles, density, and submergence. Although multiple factors impact the dispersion process, leading to complex variations in the dispersion coefficient in different scenarios, the following conclusions can be drawn.

(1) For all channels with aquatic canopies, vegetation density is one of the most crucial factors that cannot be sidetracked. Vegetation density changes the length scale of turbulent vortexes and is the main factor that impacts the dispersion in channels with canopies, where the combined action of two dispersion mechanisms, i.e., vortex-trapping dispersion and spatial velocity-shear dispersion, leads to two inverse effects of vegetation density on dispersion in emergent vegetated flows. However, in channels with submerged and suspended vegetation and the compound channels with vegetated floodplains, the increase in vegetation density enhances the variation between vegetation regions and no-vegetation regions, and the dispersion is also controlled by the large-scale coherent vortex in the interface.

(2) The submergence ratio of canopies and the depth ratio of main channels and floodplains integrally alter the profile of the longitudinal velocity in vertical (e.g., channels with submerged vegetation) and lateral (e.g., the compound channels with vegetated floodplains) directions, respectively. Studies have showed that the change in dispersion magnitude induced by vegetation density is overshadowed by the dispersion induced by this type of variation of integral velocity profiles. However, the scale of the exchange vortex in the interface of vegetation regions and no-vegetation regions is another key factor for the dispersion process. As a result of these complex effects, the review emphasized that the change of k_x with the submergence ratio and the depth ratio should be illustrated in specific scenarios.

(3) The review introduced three main methods to deduce the longitudinal dispersion coefficient, inclu-

ding concentration-based routing method, the moment method, and the velocity-based integral method, in detail. The routing method is most commonly used in experimental studies due to its high-efficiency calculation and wide applicability, whereas the moment method is constrained by the difficulty in determining the start and end of the concentration cloud and thus is more likely to be adopted in open channel flows without canopies rather than complex conditions with aquatic canopies. The integral method is a theoretical and velocity-based method, where the lateral or vertical profiles of the longitudinal velocity are complex and difficult to integrate, although the N-zone model was adopted to deal with the difficulty in the triple integral of the velocity. The other numerical methods are less commonly used because they are intensively based on amounts of experimental data. Adopting available methods based on specific conditions is necessary.

Vegetation notably impacts transport and mixing processes and can be used to control the fate of substances in the hydro-environment. Since the beginning of the 21st century, research on the key parameter k_x in channels with canopies has rapidly developed and formed general theoretical systems. However, the studies describing the interaction between vegetation and the dispersion process are not fully understood and have not been investigated completely synchronously, leading to scattered and disconnected results in different studies. Predictably, future research on this topic should address the challenges highlighted below.

(4) Present studies can qualitatively analyze the dispersion process depending on the main impacted factors, but the quantificational of the change of k_x with the variable parameters is insufficient and cannot express the complex interaction between dispersion and vegetation. Future studies should aim to derive the mathematical relation between the dispersion coefficient and the corresponding impacted factors and explore the dominant factors in different scenarios.

(5) Although studies based on rigid vegetation can express the generalized law of the dispersion process, the mathematical description of "realistic" vegetation characteristics, including vegetation spatial arrangement, vegetation flexibility, and foliated/no-foliated vegetation, is necessary to meet the study requirements of natural rivers. Furthermore, future research should address how to apply the outcomes of the descriptions of the vegetation characteristics to the model of dispersion.

(6) Most of the experimental data were observed in laboratory flume experiments, and only a few studies measured the dispersion coefficient in natural vegetated rivers. Future studies should pay more attention to the relation between flume-scale dispersion and river-scale dispersion. Clarifying the key hydraulic parameters from lab to river and proposing an expression adoptable in both lab and river scenarios will benefit river management and environmental risk assessment.

Plants preferably grow near the river bank or floodplains, and the deepest parts of the channel remain bare. In such rivers, aquatic vegetation is often arranged in patches or strips against seasons. Currently, validated predictors for estimating the influence of patchy vegetation on the dispersion coefficient are lacking, and we are aware of only two existing recent studies[41, 94] focusing on real-scale vegetation patches in compound channels. Experimental or quantitative models describing the dispersion features with the effects of real-scale plants patches are in their infancy. Addressing this gap in previous research is expected to hugely promote the development of the theory of dispersion mechanism in natural rivers in the future.

Acknowledgement

(This research received other funding agency in the public, commercial, or not-for-profit sectors.)

Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflict of interest. Wen-xin Huai is editorial board member for the Journal of Hydrodynamics and was not involved in the editorial review, or the decision to publish this article. All authors declare that there are no other competing interests.

Ethical approval: This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent: Informed consent was obtained from all individual participants included in the study.

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