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Suspended sediment concentration profile in a *Typha latifolia* canopy

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Key points

Profiles of suspended sediment concentration (SSC) were measured in a model canopy of *Typha latifolia*.

The vertical turbulent diffusivity depends on plant-generated turbulence and morphology.

A model to predict vertical diffusivity was developed, validated, and used to simulate the SSC with a random displacement model.

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Abstract

The transport of sediment in regions with vegetation plays an important role in aquatic ecosystems and landform evolution in river deltas. In this study, flow parameters and suspended sediment concentration (SSC) within an emergent canopy with real plant morphology (*Typha latifolia*) were measured in a laboratory channel. *T. latifolia* is a common marsh species with multiple thin leaves emerging from a tight bundle (culm) at the bed. The observed equilibrium SSC profile differed significantly from a Rouse profile, the classic model for SSC over bare beds. The vertical distribution of SSC was nearly uniform in the culm region of the canopy, and decreased with height in the upper canopy region of distributed leaves. The profile of SSC reflected the vertically-nonuniform turbulent diffusion, which arose from the plant morphology. A diffusivity model based on cylinder arrays was first validated with tracer data and then adapted to the *T. latifolia* morphology, providing a way to model turbulent diffusivity in marsh systems. The diffusivity model was successfully used within a random displacement model (RDM) to predict the spatial evolution and equilibrium SSC profile within the *T. latifolia* canopy.

1. Introduction

Aquatic vegetation provides important ecosystem services in rivers, lakes, wetlands, and coastal regions. It protects riverbanks and shorelines from floods and waves, provides shelter for aquatic organisms, enhances water quality, and promotes soil carbon accretion (e.g., Barbier et al., 2011; Costanza et al., 1997; Fourqurean et al., 2012; Kemp et al., 2000). During past decades, significant marsh and mangrove area has been lost from river deltas, diminishing these ecosystem services, so there is a growing interest in restoring and managing these systems (e.g., Mississippi River Delta and Mekong delta; Minderhoud et al., 2019; Nittrouer et al., 2012). To guide restoration, it is necessary to understand the interaction between flow, vegetation, and sediment transport. This study considers suspended sediment.

In bare channels, the highest suspended sediment concentration (SSC) occurs at the bed, associated with bed-generated turbulence and bed-shear stress (Jiménez, 2012). Turbulent diffusion carries sediment away from the bed (positive z direction), until an equilibrium is reached between the upward diffusive flux and downward settling flux. This equilibrium is described by the Rouse profile, which has a maximum SSC at the bed (Coleman, 1986; Rouse, 1937). In an array of emergent cylinders, Lu (2008) found that the SSC profile was similar to that observed in a bare channel, decreasing from a maximum at the bed. By assuming a constant vertical diffusivity, Lu (2008) obtained an analytical solution for SSC, which agreed with their experimental data. Similarly, Huai et al. (2019) predicted the SSC profiles in the experiment of Lu (2008) assuming a uniform diffusivity in a random displacement model (RDM).

The assumption of a vertically-uniform diffusivity is appropriate over most of the water depth within a uniform

cylinder array (e.g., Lightbody & Nepf, 2006; Nepf et al., 1997; Nepf, 1999). Tseng and Tinoco (2020) noted that the diffusivity is elevated in a thin boundary layer close to the bed and used this to develop a two-region model to predict the SSC profile in a cylinder array. However, real vegetation has a morphology distinct from uniform cylinders, which can produce significant vertical variation in velocity and turbulence (Tinoco, 2011; Xu & Nepf, 2020; Zhang et al., 2021), which, in turn, will impact the SSC profile. For example, Li et al. (2020) observed a maximum SSC at the top of a submerged plastic canopy, not at the bed, and this was attributed to elevated turbulence, and thus diffusivity, associated with the shear-layer at the top of a submerged canopy. Similarly, Huai et al. (2019) predicted profiles of SSC measured with a submerged array of cylinders using a diffusivity model that represented the shear-layer turbulence. Vertical variation in emergent vegetation morphology will similarly impact the vertical distribution of turbulence, diffusivity, and SSC. Combining measurements and simulations of SSC, the present study considered these dependences for the marsh plant *Typha latifolia*, which has multiple thin leaves emerging from a tight culm at the bed (Figure 1).

2. Methods

2.1 Experimental setup

The experiments were conducted in a 24-m long, 38-cm wide recirculating flume with zero bed slope (Figure 1a). The model plant, *Typha latifolia*, consisted of long sword-shaped leaves, which were bundled into a culm at the base (Figure 1b). Each plastic plant consisted of 40 leaves, with lengths $l_1 = 30$ to 40 cm and widths $w_1 = 0.1$ to 0.4 cm, which was the same as real *T. latifolia* leaves (Liu et al., 2017). The plants were placed in a staggered arrangement in PVC baseboards (Figure 1b). Once installed, the canopy height was 38 ± 2 cm. The length (L) and width (W) of the canopy was 16 m and 0.38 m, respectively. The area density, m , was 119 plants/ m^2 , and the depth-average solid volume fraction $\phi = 0.0057$ to 0.0065, depending on depth. Plant characteristics are shown in Table 1. Importantly, unlike a cylinder array, the *T. latifolia* canopy was vertically non-uniform. Figure 1c shows the vertical profiles of plant frontal area per cm vertical interval, A (cm^2/cm), which displays the vertical non-uniformity of *T. latifolia*. Due to this non-uniformity, the depth-average frontal area per volume $\langle a \rangle_z = mA_f/H$, in which A_f is the cumulative frontal area of one plant, $A_f = \int_0^H A dz$, varied with water depth (Table 1).

Figure 1. (a) Side view of channel. Not to scale. Flow is left to right, with $x = 0$ at leading edge of canopy, which was 16 m long. Particles were released from a nozzle upstream of the canopy. Velocity was measured with an ADV. SSC was measured with four optical backscatter sensors (OBS), mounted in pairs on two vertical rods. (b) Photo of *T. latifolia* canopy. (c) *T. latifolia* frontal area per cm vertical interval, A (cm^2/cm) (from Xu & Nepf, 2020).

The inlet to the channel was located 2 m upstream of the canopy, and flow was controlled by a variable speed pump. The flow rate was monitored by an electromagnetic flowmeter mounted on the return pipe. The instantaneous velocity (u, v, w), corresponding to x (longitudinal), y (lateral), and z (vertical) directions, respectively, was recorded using a Nortek Vectrino Acoustic Doppler Velocimeter (ADV). Spikes in the velocity record were removed by a MATLAB code, which used the acceleration threshold method described in Goring and Nikora (2002). Vertical profiles were measured with a resolution of 1 cm. Four lateral positions between plant rows were chosen to capture the lateral variation within the canopy. The measurements were first time-averaged, denoted by an overbar, then laterally-averaged, denoted by $\langle \rangle$, and finally depth-averaged, denoted by $\langle \rangle_z$. Additional details for the velocity measurements can be found in Section 3.3.1 in Xu and Nepf (2020). The velocity was measured at $x = 8$ m (i.e., mid-length along the canopy, Figure 1a). Based on a previous study with the same canopy, the velocity and turbulence were fully developed at 0.58 m from the leading edge. Three water depths ($H = 20, 30$, and 35 cm) were considered (Table 1). For each water depth, three to four different flow discharges were chosen, producing ten cases. The channel-average velocity U ranged from 4.8 to 18.5 cm/s, which was consistent with values measured in the field (e.g., Leonard & Luther, 1995; Naden et al., 2006). Plant reconfiguration (bending) was not considered, and for the flow and depth conditions considered here, the model plants did not reconfigure (see discussion in section 4.5 of Xu & Nepf, 2020). The water surface slope, S , was measured with two wave gauges with 0.2 mm accuracy and 1000 Hz sampling rate, which were located at $x = 0.5$ m and 14.5 m (Table 1, and Supporting Information).

Table 1. Summary of experiment conditions and best-fit diffusion scale factor

Run	H (cm)	$U \pm \sigma_U^a$ (cm/s)	$\langle a \rangle_z^b$ (m ⁻¹)	ϕ	x -location of SSC measurements (m)	$S \pm \sigma_S^c$ (10 ⁻³)	Best-fit α_z at equilibrium
1.1	20	7.6 ± 0.3	3.10	0.0057	1.0, 3.1, 13.2, 14.1	1.3 ± 0.1	2.5
1.2	20	9.4 ± 0.5	3.10	0.0057	0.5, 1.0, 1.9, 3.1, 13.2, 14.1	1.6 ± 0.1	2.0
1.3	20	13.1 ± 0.6	3.10	0.0057	13.2, 14.1	3.6 ± 0.3	2.0
1.4	20	18.5 ± 1.1	3.10	0.0057	13.2, 14.1	7.7 ± 0.5	1.5
2.1	30	6.4 ± 0.3	3.85	0.0064	13.2, 14.1	1.2 ± 0.1	4.0
2.2	30	9.4 ± 0.5	3.85	0.0064	0.5, 1.0, 1.9, 3.1, 13.2, 14.1	2.9 ± 0.2	3.0
2.3	30	13.9 ± 0.6	3.85	0.0064	13.2, 14.1	5.6 ± 0.5	2.5
3.1	35	4.8 ± 0.2	3.94	0.0065	13.2, 14.1	0.8 ± 0.1	3.0
3.2	35	7.6 ± 0.4	3.94	0.0065	1.0, 3.1, 13.2, 14.1	1.9 ± 0.2	3.5
3.3	35	11.4 ± 0.5	3.94	0.0065	13.2, 14.1	3.3 ± 0.2	3.0

^a Channel-average velocity U determined from the flowmeter was equal to the velocity $\langle \bar{u} \rangle_z$ measured with the ADV. The uncertainty σ_U was associated with fluctuations in the flowmeter reading. ^b Depth-average frontal area per volume $\langle a \rangle_z = mA_f/H$. A_f is the cumulative frontal area of one plant, $A_f = \int_0^H Adz$. ^c Uncertainty in slope σ_s arose from fluctuations of water surface.

The model sediment consisted of silica particles with density $\rho_s=2.5$ g/cm³ and median diameter $D_{50}=29$ μ m (Potters Industries, Valley Forge, PA). The particle size was chosen to ensure that the sediment could be suspended within the range of possible flow conditions. The particle size distribution (Figure S2 in Supporting Information) was measured using a Beckman Coulter laser diffraction instrument (Follett & Nepf, 2018). The settling velocity, w_s , was estimated using Eqn. 4 in Ferguson and Church (2004). For $D_{50} = 29$ μ m, $w_{s50}=0.067$ cm/s (Supporting Information). Particles were released at mid-depth and slightly upstream of the canopy, at $x = -0.15$ m (Figure 1a). Before each experiment, 700 g of particles were mixed with 10 L water to form a dilute solution. The particle slurry was continuously mixed in a 15-L bucket using a magnetic stirrer and injected continuously through a 2-mm nozzle using a peristaltic pump (Figure 1a). A tee-shaped nozzle directed the slurry in the $\pm y$ direction. The slurry discharge rate, Q_{in} was 12.6 ± 1.9 ml/s.

The suspended sediment concentration was measured using four optical backscatter sensors (OBS, Seapoint Sensors Inc.). A prepared slurry concentration, ranging from 0 - 500 mg/L, was used to calibrate the OBS output voltage with concentration (see Supporting Information). Pairs of OBSs were mounted on a thin rigid rod (Figure 1a), which moved vertically. SSC was measured simultaneously at two longitudinal positions. A preliminary test experiment was conducted for each flow condition to determine the time at which stationary SSC conditions were reached (Figure S4 in Supporting Information). The OBS measurement began when the particle release began and measured continuously at 20Hz for the entire duration of the release (12 min). This time allowed particles to recirculate in the flume at least twice. The SSC record revealed the time period of steady state SSC conditions. In subsequent runs with the same flow conditions, the vertical profile of SSC was measured within the steady time-period by vertically moving the rigid rod to obtain measurements at eight vertical positions. Each case was repeated to assess method uncertainty. To observe the longitudinal evolution of SSC, multiple experiments were conducted for the same flow condition, with the OBS at different streamwise positions (Table 1).

Fine particles can be captured directly by plant leaves, and other plant surfaces (Kretz et al., 2020). This on-plant sedimentation decreases with increasing flow velocity or collector Reynolds number (Fauria et al., 2015; Purich, 2006; Wingenroth et al., 2021). At the leaf scale, Kretz et al. (2019) observed that adaxial pubescence and enhanced sedimentation on leaves. However, for the flow conditions (relatively high flow velocity), plant characteristics (low

canopy density and smooth leaves without pubescence), and absence of biofilm in present study, the on-plant sedimentation was negligible. This was confirmed by the fact that the measured flux of particles in the water column agreed with the injected flux, indicating that deposition of any sort (to the bed or to the plant surfaces) was small enough to be neglected in the experiments.

2.2 Random displacement model

A 2D (streamwise, x , and vertical, z) random displacement model was used to simulate the transport of individual particles. Within each time-step, Δt , particles were displaced by time-mean advection in x and turbulent diffusion in z (Gardiner, 1985). Assuming a high streamwise Peclet number, the longitudinal diffusion was neglected (Taylor, 1953). The particle position at time step $i+1$ was described as in Tsai et al. (2020):

$$x_{i+1} = x_i + \langle \bar{u}(z_i) \rangle \Delta t \quad (1)$$

$$z_{i+1} = z_i + \left(\frac{\partial K_z}{\partial z}(z_i) - w_s \right) \Delta t + \sqrt{2K_z(z_i)\Delta t} R \quad (2)$$

in which K_z is the sediment diffusivity in z . The term $\partial K_z / \partial z$ is a pseudo-velocity needed to prevent the artificial accumulation of particles in the regions of low diffusivity (Durbin, 1983; Wilson & Yee, 2007). R is a random variable with standard Gaussian distribution (zero mean and unit variance). In this study, sediment diffusivity K_z was assumed equal to turbulent diffusivity D_z , since the particles were fine enough for this assumption (Absi, 2010). The time-step, Δt , was chosen so that the vertical particle trajectory within each time-step was much smaller than the scale of vertical gradients in the diffusivity and velocity (Follett et al., 2016; Israelsson et al., 2006). Huai et al. (2019) suggested the length scale $0.05H$ for emergent vegetation.

$$\Delta t < \min \left(\frac{0.05H}{\left| \frac{\partial D_z}{\partial z} - w_s \right|_{\max}}, \frac{(0.05H)^2}{(D_z)_{\max}} \right) \quad (3)$$

Simulations with different Δt , ranging from 0.01s to 0.1s, confirmed that the solution was insensitive to time step within this range (varied by less than 5%). The time-step was set as 0.05s.

The measured flux of suspended particles within the canopy, $\langle C \rangle_z \cdot W \cdot H \cdot U$, agreed with the injected flux ($C_{in} Q_{in}$) to within 10%. This confirmed that no deposition occurred. This was represented in the RDM using a no-flux (reflecting) boundary condition at the channel bottom. The same boundary condition was applied at the water surface, because particles cannot pass through or collect at the surface (Huai et al., 2019; Murphy, 2006):

$$z_i = -z_i, \quad z_i < 0 \quad (\text{bottom boundary}) \quad (4)$$

$$z_i = 2H - z_i, \quad z_i > H \quad (\text{water surface}) \quad (5)$$

Within the RDM 10,000 particles were released at the same point that particles entered the canopy in the experiment,

and the RDM was run for 6000 steps (300s, $\Delta t = 0.05$ s), which simulated the duration of the physical experiment. Comparison of SSC profiles simulated with D_{50} and with a distribution of sizes suggested that D_{50} was a good representative size (Figure S5 in Supporting Information). Each simulation was repeated for 10 realizations.

To translate the discrete particle positions into a concentration profile, the water depth was divided into $N = 50$ layers, and the concentration, C , was calculated as the number of particles per layer height.

The adaption time, T_a , describes the time-scale needed to reach an equilibrium profile of concentration, defined by the balance of upward diffusion and downward settling. Equilibrium was reached in the RDM when the vertical profile of concentration changes by less than 2% between time-steps. Specifically, the mean percentage error (MPE) summed over the 50 vertical positions was calculated between the current i and previous $i - 1$ time-step,

$$MPE(i) = \frac{\sum_{j=1}^N \frac{|C_j(i-1) - C_j(i)|}{C_j(i)}}{N} \times 100\% \quad (6)$$

in which $C_j(i)$ is the sediment concentration in j^{th} layer at the i^{th} time step. The adaption time, T_a , was defined at the time-point when MPE was less than 2%.

2.3 Parameterization of Transport Parameters in *Typha latifolia*

The RDM was run with the measured velocity profile $\langle \bar{u} \rangle$ and a turbulent diffusion based on the model of Tanino and Nepf (2008). Turbulent diffusivity can be described in terms of a turbulent velocity ($\sqrt{k_t}$) and length-scale (l_t),

$$D = \alpha \sqrt{k_t} l_t \quad (7)$$

in which l_t is the integral length-scale, k_t is the turbulent kinetic energy (TKE) per fluid mass, and α is a scale constant. Within a canopy, l_t , k_t , and α are shaped by vegetation-generated turbulence (e.g., Nepf, 2012). Models for α , l_t and k_t have been developed and validated for an array of rigid, circular cylinders (Tanino & Nepf, 2008). For the *T. latifolia* canopy, l_t equals the culm diameter, d , near the bed and the leaf width, w near the surface, with a smooth transition between (see Eqn. 16 in Xu & Nepf, 2020, repeated here for convenience).

$$l_t = \begin{cases} d = 1.5, & z < 10 \\ 3.6 - 0.19z, & 10 \leq z < 17 \\ w = 0.2 & z \geq 17 \end{cases} \quad (8)$$

All units in Eqn. 8 are in cm. Note that this relationship represents the average profile measured over many water depths. The turbulent kinetic energy k_t also varies over the *T. latifolia* canopy height (see Eqn. 17 in Xu and Nepf, 2020),

$$k_t(z) = \gamma^2 \left(C_D \frac{a l_t}{2(1-\phi(z))} \right)^{2/3} \langle \bar{u} \rangle^2 \quad (9)$$

in which the frontal area per canopy volume (a , Figure 1c), solid volume fraction (ϕ), and velocity, $\langle \bar{u} \rangle$, are all

functions of z . Strictly, Eqn. 9 should use the form drag coefficient (C_D^{form} , Tanino & Nepf, 2008). However, at typical Reynolds numbers in a canopy, the viscous drag is small compared to the form drag, and $C_D^{form} \approx 0.9C_D$ (for plant element $Re > 200$, Etminan et al., 2018), making it reasonable to simplify Eqn. 9 using $C_D \approx C_D^{form}$. The scale coefficient for *T. latifolia*, $\gamma^2 = 1.6 \pm 0.4$ (Xu & Nepf, 2020), is slightly larger than that determined for an array of rigid cylinders ($\gamma^2 = 1.1 \pm 0.2$, Eqn. 3.33 in Tanino, 2008), suggesting that γ^2 may be sensitive to the plant morphology. The present study considered whether predictions of l_t and k_t from Eqns. 8 and 9 could be used in Eqn. 7 to predict the turbulent diffusivity within a *T. latifolia* canopy.

For a canopy of cylinders with diameter d and the marsh-relevant solid volume fraction $\phi < 0.03$, the mixing length-scale $l_t = d$, and α depends on both ϕ and the cylinder arrangement (random versus regular array, Tanino & Nepf, 2008). In particular, α reflects the fraction of canopy space in which the local center-to-center spacing s_{nc} between cylinders is more than $2d$, $P_{s_{nc}>2d}$, because only these regions can support eddies $l_t = d$. For a random array $P_{s_{nc}>2d} = f(\phi)$, but for a staggered or square array in this range, $P_{s_{nc}>2d} = 1$. Note that Tanino and Nepf (2008) considered lateral diffusivity, which we note with subscript y . The function $\alpha_y = F(\phi)$, based on Eqn. 2.16 and Appendix A in Tanino and Nepf (2008), is shown in Figure 2. Additional details are provided in Section S7 in the Supporting Information. Within a cylinder array, measured vertical diffusivity has been shown to be smaller than lateral diffusivity, $D_z \approx 0.25D_y$ for $\phi=0.006$ to 0.053 (Nepf et al., 1997), which is consistent with the vertical orientation of the array elements. However, field measurements show $D_z \approx D_y$ in *Spartina alterniflora*, which has a morphology similar to *T. latifolia* (Lightbody & Nepf, 2006; Tarrell, 1997). The isotropic diffusion was attributed to the varied orientation of real plant elements.

Figure 2. Diffusivity scale constant $\alpha_y = D_y/\sqrt{k_t}d$ for lateral turbulent diffusion in an array of cylinders with diameter, d , based on Eqn. 2.16 and Appendix A in Tanino and Nepf (2008). Solid curve is a regular array with $P_{s_{nc}>2d} = 1$. Dashed curve is for a random array with $P_{s_{nc}>2d}$ described in Eqn. A21 in Tanino and Nepf (2008). Vertical gray bar indicates the *T. latifolia* canopy in this study, with $\phi=0.0057$ to 0.0065 , Table 1.

3. Results and discussion

3.1 Validation of vertical diffusivity model

3.1.1 Transport of a neutrally buoyant tracer in a cylinder array

To validate the diffusivity model (Eqns. 7, 8, and 9) and the RDM method, the model was used to simulate a laboratory experiment that measured dye transport (Rhodamine WT) in a cylinder array consisting of two layers of different cylinder density (Lightbody & Nepf, 2006). The dye was dilute enough to be neutrally buoyant, so that $w_s = 0$ in

Eqn. 2. Cylinders with diameter $d=0.64$ cm and two lengths were arranged randomly in a predrilled plastic sheet, creating a canopy with two layers: a sparser lower layer with $m_1=300$ stems/m² and $\phi=0.0097$, and a denser upper layer with $m_2=600$ stems/m² and $\phi=0.0193$ (Figure 4-10 in Lightbody, 2004). The dye was released at mid-width and 0.5 cm from the channel bed. Velocity and dye concentration were measured using an ADV and a Rhodamine fluorometer, respectively. Vertical diffusivity D_z was determined in their study by fitting measured concentration profiles to analytical solutions for vertical concentration profiles (Table 2, the third column).

Table 2. Flow characteristics in Lightbody (2004)

H (cm)	U (cm/s)		Measured D_z (cm ² /s)		Predicted D_z from Eqn.7	
	Lower layer	Upper layer	Lower layer	Upper layer	Lower layer	Upper layer
20 ± 1	5.2 ± 0.1	3.4 ± 0.1	0.25 ± 0.16	0.04 ± 0.08	0.24 ± 0.08	0.09 ± 0.04

Based on the Tanino model for a random cylinder array $\alpha_y = 0.90$ and 0.77 for $\phi=0.0097$ and $\phi=0.0193$, respectively. For a cylinder array, we expect $\alpha_z = 0.25\alpha_y$, yielding $\alpha_z = 0.23$ and 0.19 , respectively. Using these scale factors, the measured k_t , and $l_t = d$ in Eqn. 7, the vertical diffusivity D_z was predicted to be 0.24 ± 0.08 cm²/s for lower layer and 0.09 ± 0.04 cm²/s for upper layer, which agreed with the measured diffusivity within uncertainty (Table 2). Further, this diffusivity accurately predicted the measured concentration profiles. Specifically, 10000 particles were released at 0.5 cm from the simulated bed, consistent with the experimental setup, and the simulation was run until steady-state was achieved at four distances from the release ($x = 50, 100, 200$, and 300 cm). The simulation was run 10 times to provide an assessment of random error. At each longitudinal position, the ensemble average concentration from the 10 realizations agreed with the measured concentration to within less than 7.5%, which validated the vertical diffusivity model for a canopy of cylinders (Figure 3a).

Figure 3. (a) Simulated concentration (dashed lines) and measured concentration (symbols, from Lightbody, 2004). The vertical coordinate was normalized by water depth, H , and the concentration was normalized by C_a , the reference concentration at $z = 0.1H$. Standard error among ten realizations ranged from 1% to 4%. The gray dashed line denotes the interface between two layers. At each position the simulated concentration agreed with the measured concentration to within 7.5% (b) Comparison of equilibrium SSC profile simulated with RDM and measured by Lu (2008). The gray area denotes the uncertainty of RDM results. C_a is the reference concentration at $z=0.5H$.

3.1.2 Transport of suspended sediment in a cylinder array

The diffusivity model and RDM method were also validated for sediment transport using data from Lu (2008), who measured suspended sediment concentration in a square array of circular cylinders with diameter $d=0.6$ cm and solid

volume fraction $\phi = 0.028$. The plastic particles were 217 μm with $w_s=0.162$ cm/s. Lu et al. (2008) circulated the particles long enough to obtain an equilibrium SSC profile. They measured velocity and concentration using an ADV and a siphon, respectively. The velocity was vertically uniform, as expected for a uniform cylinder array (Figure 6-7 in Lu, 2008).

Table 3. Flow and canopy characteristic in Lu (2008)

Case	H (cm)	U (cm/s)	ϕ	S (10^{-3})	$k_t(\text{cm}^2/\text{s}^2)$	α_z	$D_z(\text{cm}^2/\text{s})$
D18-3	18.0	16.9	0.028	13.6	19.9 ± 3.8	0.65	1.7 ± 0.3

The turbulent kinetic energy, $k_t=19.9 \pm 3.8$ cm^2/s^2 was determined from measured velocity and Eqn. 9. For a square array with $\phi = 0.028$, $\alpha_y=2.6$ (Figure 2), and within a cylinder array we expect $\alpha_z=0.25\alpha_y=0.65$. From these estimates, Eqn. 7 predicted the turbulent diffusion $D_z = 1.7 \pm 0.3$ cm^2/s (standard error propagated from TKE prediction). The equilibrium SSC profile simulated using this predicted diffusivity agreed with the measured profile to within the uncertainty (based on standard error among 10 realizations of RDM, gray area in Figure 3b), indicating that the diffusivity prediction (Eqn. 7) and RDM method had good performance simulating suspended sediment transport. In conclusion, results presented in this section have validated the vertical diffusivity model for cylinder arrays (Eqns. 7, 8, 9) with both neutrally-buoyant tracer and sediment. However, the extension of this model to more complex morphology must still be considered, which is the goal of the remainder of this paper.

3.2 Measured SSC profiles in *Typha latifolia* canopy

The concentration profiles measured at $x = 13.2\text{m}$ and 14.1m (open and filled symbols, respectively, Figure 4a) differed by less than 6%, which was comparable to the uncertainty, indicating that the SSC has reached the equilibrium profile by this point. For further analysis, the SSC at these two positions were averaged to represent the equilibrium profiles, which are presented for flow depths $H=20$ cm and 35 cm in Figure 4b and 4c, respectively. For comparison, the profile predicted for a bare channel with the same velocity (Rouse profile) was plotted with dashed curves. For the bare channel, the vertical turbulent diffusion has a parabolic distribution (e.g., Cellino, 1998):

$$D_z = \kappa u_* z \left(1 - \frac{z}{H}\right) \quad (10)$$

in which κ ($=0.4$) is the von Karman constant and u_* is the friction velocity, estimated from the linear distribution of Reynolds stress in the bare channel. For the same channel velocity and depth, SSC profiles in the *T. latifolia* (symbols) differed significantly from the Rouse profile. Within the *T. latifolia*, SSC was close to vertically uniform in the lower culm region ($z < 15$ cm), which corresponded to nearly the full flow depth for $H = 20$ cm (Figure 4b).

With greater water depth ($H = 35$ cm, Figure 4c), SSC decreased with distance from the bed in the upper region of the canopy ($z > 15$ cm). A more uniform SSC profile in the *T. latifolia*, compared to bare channel, can be attributed to vegetation-induced turbulence, which increased turbulence intensity by nearly seven-fold, relative to a bare channel with same channel-average velocity (Figure 4e). Further, the shape of the SSC profile can be correlated with vertical variation in k_t and l_t (Figure 4e and 4f). Specifically, l_t was higher in the lower canopy ($z < 15$ cm), where turbulence length-scale was set by the culm diameter, compared to the upper canopy ($z > 15$ cm), where l_t was set by the leaf width. Similarly, k_t was higher in the lower canopy ($z < 15$ cm), where the local velocity was higher (Figure 4d). Higher values of k_t and l_t in the lower canopy would be associated with higher values of turbulent diffusivity (Eqn. 7), which was consistent with a more uniform SSC in the lower region of the canopy, compared to the upper canopy (Figure 4c).

Figure 4. (a) SSC within *T. latifolia* canopy at $x=13.2$ m (open symbols) and 14.1 m (filled symbols) for Case1.1 (circles, $H=20$ cm, $U=7.6$ cm/s) and Case3.2 (diamonds, $H=35$ cm, $U=7.6$ cm/s). Subplots (b) and (c) show equilibrium SSC profiles in *T. latifolia* for (b) $H=20$ cm and (c) $H=35$ cm. The dashed lines show the SSC profile in bare channel estimated with Rouse formula. (d) measured values of velocity, $\langle \bar{u} \rangle$, and (e) measured TKE, $\langle k_t \rangle$, each normalized by the channel average velocity U , and (f) integral length-scale, l_t for Case 3.1, with $H = 35$ cm. Open triangles represent the bare channel with the same flow condition (legend in subplot d).

The vertical distribution for SSC became more uniform as the channel-average velocity increased (Figure 4c). Specifically, the bed to surface concentration difference decreased from 0.71 to 0.36 as velocity increased from 4.8 cm/s (blue dots, Case 3.1) to 11.4 cm/s (red dots, Case 3.3). This suggested that vertical diffusivity increased with velocity, which was consistent with the scaling $D_t \sim \sqrt{k_t} \sim U$. For $H = 20$ cm, a velocity dependence was not observed (Figure 4b), because in each of these cases the diffusivity was high enough to produce an essentially uniform SSC profile. For example, the depth-average diffusivity, $\langle D_z \rangle_z = 5.6$ cm²/s, for Case 1.1 was higher than the value, $\langle D_z \rangle_z = 2.9$ cm²/s, for Case 3.1. Furthermore, the diffusivity profile was much more uniform over depth for $H=20$ cm (Case 1.1, Figure 6b) than for $H = 35$ cm (Case 3.1, Figure 6d).

3.3 Canopy drag coefficient

The *T. latifolia* drag coefficient, C_D , is needed to predict k_t and thus turbulent diffusivity (Eqns. 7 and 9). The drag coefficient was estimated from the momentum balance and measured water surface slope S (Table 1). In sparse, emergent canopies, viscous, Reynolds, and dispersive stresses are typically much smaller than canopy drag (Lightbody & Nepf, 2006; Xu & Nepf, 2020), so that the momentum equation for fully-developed, steady flow can

be simplified to a balance of canopy drag and pressure.

$$0 = \underbrace{gS}_{\text{pressure forcing term}} - \underbrace{\frac{1}{2} \frac{C_D a}{(1-\phi)} U^2}_{\text{vegetation drag}} \quad (11)$$

Xu and Nepf (2020) determined a drag coefficient for an individual plant using a force transducer to measure the drag on an individual plant within a canopy. To explore whether this plant-scale drag coefficient represents the distributed drag within a canopy (canopy-scale drag coefficient, based on Eqn. 11), C_D estimated by the two methods are compared in Figure 5. The plant-scale C_D agreed with the canopy-scale C_D to within 10%, and $C_D(\text{plant-scale}) = 1.04 \pm 0.06 C_D(\text{canopy-scale})$, indicating that C_D estimated by Eqn. 11 and C_D measured on an individual plant were interchangeable. This indicated that the drag (energy loss) associated with shear generated in the spaces between plants was negligible. This supports the application of plant-scale drag for use in distributed drag models.

Figure 5. Comparison of canopy-scale C_D , determined from Eqn. 11, and plant-scale C_D , based on force measured on an individual plant within a canopy (from Xu & Nepf, 2020). The horizontal error bars arise from the uncertainty of water surface slope. The vertical error bars are associated with replicate measurements of force on the individual plant. The dashed line represents the 1:1 line.

3.4 Diffusivity in a *Typha latifolia* canopy

The SSC profile was simulated using the RDM with a range of diffusivity scale factors in Eqn. 7, $\alpha_z = 0.5$ to 4.0, and these were compared to the measured profiles (Figure 6a and 6c). As α_z increased, the simulated SSC decreased near the bed and increased in upper canopy, consistent with an increase in vertical turbulent diffusion. The difference between simulated and measured SSC was quantified with the mean percentage error (Eqn. 6, inset graphs in Figure 6). The trend of MPE with α_z was similar for all cases (Figure S7 in Supporting Information), decreasing rapidly between $\alpha_z = 0.5$ to 1, and reaching a minimum error of 1.2% to 4.8% for α_z between 1.5 and 4 (Table 1). The best-fit α_z differed with water depth. For $H = 20$ cm, best-fit α_z ranged from 1.5 to 2.5, with mean 2.0 ± 0.4 . For $H = 30$ cm and 35 cm, best-fit α_z ranged from 2.5 to 4.0, with mean 3.1 ± 0.5 . There was no dependence of α_z on velocity (Table 1), which was consistent with Tanino's description of α_z as a function of canopy morphology and the fact that no reconfiguration was observed (Section 2.3 in Tanino & Nepf, 2008).

The profile of vertical diffusivity D_z corresponding to the best-fit α_z is presented in Figures 6b and 6d. The diffusivity in a bare channel (Eqn. 10) with the same channel velocity was included with a dashed curve, which illustrated the significant degree to which the canopy enhanced the vertical diffusivity. For example, in Cases 1.1 and 3.1, the depth-average D_z with *T. latifolia* was 5 to 10 times higher than that for bare channel. The canopy also changed the shape of the diffusivity profile. The diffusivity was highest in the culm region near the bed, corresponding

to the region of maximum turbulent kinetic energy k_t and integral length-scale l_t (Figure 4e and 4f). However, it is worth noting that the comparison in the present study assumed the same velocity in the vegetated and bare channel, whereas in reality the velocity will be lower in the vegetation. For a fixed water surface slope driving flow into the vegetation, velocity decreases with increasing stem density. The decreasing velocity dominates the augmented turbulence generation (Eqn. 9), such that turbulence decreases with increasing stem density (see Figure 4 in Yang and Nepf, 2018), from which Eqn.7 predicts a decrease in vertical diffusivity with increasing stem density.

Figure 6. Subplots (a) and (c) compare measured equilibrium SSC profile (open circle) and RDM simulation (dashed lines, from blue to red $\alpha_z = 0.5$ to 4). Concentration normalized by the depth-average $\langle C \rangle_z$. (a) Case 1.1: $H=20\text{cm}$, $U=7.6\text{ cm/s}$, (c) Case 3.1: $H=35\text{cm}$, $U=4.8\text{ cm/s}$ (legend in subplot a). Inset graph shows mean percentage error (MPE) between measured and simulated concentration as a function of α_z . Subplots (b) and (d) are vertical profiles of diffusivity using best-fit α_z in *T. latifolia* canopy (open triangle) and bare channel (Eqn. 10, dashed lines) for (b) Case 1.1 and (d) Case 3.1 (legend in subplot b).

To further explore the diffusivity model, the streamwise evolution of SSC profiles was simulated and compared to the measured concentration at $x = 0.5, 1.0, 1.9, 3.1\text{ m}$. (Figure S9 in Supporting Information). Because the evolving SSC profiles involved a wider range of sediment vertical distribution, it provided a more robust assessment of best-fit α_z (Table 4). For the smallest depth (occupied mostly by the culm), the best-fit alpha based on SSC spatial evolution was $\alpha_z=1.0 \pm 0.4$, which was smaller than that inferred from equilibrium SSC, $\alpha_z=2.0 \pm 0.4$. However, for the larger depths (which included both culm and leaves), the best-fit from SSC spatial evolution, $\alpha_z = 2.8 \pm 0.6$, was the same within uncertainty to that based on the equilibrium profile, $\alpha_z=3.1 \pm 0.5$.

Table 4. Best-fit α_z based on spatial evolution and equilibrium SSC profile

Run	H (cm)	distance from leading edge (m)	Top of particle plume (cm)	Best-fit α_z at corresponding x	Best-fit α_z at equilibrium
1.1	20	1.0, 3.1	13, 20	0.5, 1.5	2.5
1.2	20	0.5, 1.0, 1.9, 3.1	11, 15, 18, 20	0.5, 1.0, 1.0, 1.5	2.0
2.2	30	0.5, 1.0, 1.9, 3.1	25, 30, 30, 30	3.0, 3.0, 2.0, 2.0	3.0
3.2	35	1.0, 3.1	32, 34	3.5, 3.0	3.5

The fitted α_z values fell within expected values based on the modified Tanino model, suggesting that this model can predict α_z for natural canopies. Specifically, the culm region of the canopy (Figure 7a), has a geometry similar to a staggered array of vertical cylinders. For a staggered array of cylinders, previous studies have shown $\alpha_z \approx 0.25\alpha_y$

(Nepf et al., 1997), and for $\phi = 0.0057$ (Table 1) $\alpha_y = 3.3$ (Figure 2), such that $\alpha_z = 0.25\alpha_y = 0.83$. Considering only profiles for which the particle plume was isolated within the culm region (plume height < 20 cm in Table 4), the best-fit values yielded the average $\alpha_z = 0.75 \pm 0.14$ (Table 4), which agreed with the model prediction. When the water depth was larger ($H = 30$ and 35 cm), the sediment interacted with the upper canopy of leaves with varied orientation, for which previous studies have suggested $D_z \approx D_y$ (Lightbody & Nepf, 2006; Nepf, 1999). Then, from Figure 2, we predict $\alpha_z = \alpha_y = 3.3$. Considering the profiles for which the sediment interacted with the upper canopy (plume height > 20 cm), the average $\alpha_z = 2.9 \pm 0.2$ (Table 4), which was close to the predicted value ($\alpha_z = 3.3$). This agreement supports the hypothesis in Lightbody and Nepf (2006) that leaves with varied orientation generate an isotropic turbulent diffusion ($D_z \approx D_y$). Further, the best-fit α_z increased with increasing plume height, consistent with an increasing contribution of the leaf region (Figure 7c). These observations suggested that the diffusion scale factor had a dependence on water depth, due to the range of morphology included for different depths. The following values of α_z , dependent on water depth, are recommended for the *T. latifolia* canopy (also dashed lines in Figure 7c).

$$\alpha_z = \begin{cases} 0.25\alpha_y, & H < 15 \text{ cm} & (\text{culm}) \\ (0.08H - 0.9)\alpha_y, & 15 \text{ cm} \leq H < 25 \text{ cm} & (\text{transition}) \\ \alpha_y & H \geq 25 \text{ cm} & (\text{leaves}) \end{cases} \quad (12)$$

The three regions (culm, transition, leaves) were distinguished by three linear regions within the profile of frontal area of *T. latifolia* (red lines in Figure 7b). To apply this profile to other canopies, one would need to identify the vertical extend of the culm-dominated and leaf-dominated regions based on plant morphology. Note that Eqn. 12 defines a constant value of α_z as a function of water depths (H), but we also considered the impact of α_z variation over depth (z). However, this additional level of detail did not significantly impact the simulation (see Supporting Information, S10), indicating that a constant $\alpha_z = f(H)$ is adequate for representing the vertical variation in diffusivity (Eq. 7).

Figure 7. (a) Definition of morphology regions within a *T. latifolia* canopy. Near the bed, leaves are tightly clustered in culms, resembling vertical cylinders. Near the top of the canopy, leaves have varied orientation. (b) Vertical profile of *T. latifolia* frontal area per cm vertical interval, A [cm^2/cm], shown with black dots. Three regions were distinguished by linear regions within the frontal area profile, shown with red lines. (c) The vertical diffusion scale factor α_z varied with water depth. The dashed lines are Eqn. 12. The blue, gray, and red symbols are the best-fit α_z from RDM simulations with $H = 20$ cm, 30 cm, and 35 cm, respectively. The vertical position of each symbol corresponds to the top of the plume (i.e., Table 4), reflecting the depth over which the plume has been mixed, and thus the vertical domain over which diffusivity has acted on the plume.

3.5 Adaption time of SSC in *Typha latifolia* canopy

When water carrying suspended sediment enters a marsh, the SSC profile adjusts to the new vegetated flow condition.

It is useful to know the time-scale for this adjustment, called the adaption time, as this predicts the distance from the

marsh edge that a new equilibrium SSC profile will evolve, $X_a = U T_a$. In addition, this provides guidance for choosing the run time for numerical simulations. The adaptation time was determined from the RDM using the mean percentage error (MPE, Eqn. 6) in the concentration profile. At each time step the MPE of SSC at the current i and previous $i-1$ time step was calculated. When MPE was less than 2%, the SSC was assumed to reach the equilibrium state and this defined the adaptation time, T_a .

For channels without vegetation and fine sediment (small sediment Peclet Number, $P_e = w_s H / D_z < 1$), previous studies have found T_a scales with the diffusivity and water depth (Chatwin, 1972; Fischer, 1973, Prandle, 1997; Pritchard, 2006),

$$T_a = \beta \frac{H^2}{\langle D_z \rangle_z} \quad (13)$$

in which $\langle D_z \rangle_z$ is the depth-averaged vertical diffusivity and β is a scale coefficient. The RDM simulations indicated the same scaling also applied within the *T. latifolia* canopy (Figure 8), with $\beta = 0.41 \pm 0.09$, which was consistent with the value of β suggested in Fischer (1973). For coarse particles (large P_e), the adaption time-scale would be set by the settling time, $T_a \sim H / w_s$ (Pritchard, 2006), since the gravity of particle would dominate the adaption process.

Figure 8. Comparison between adaptation time T_a and diffusion time-scale $H^2 / \langle D_z \rangle_z$. Blue to red colors represent increasing velocity U . The vertical error bars reflect the standard error among 10 RDM simulation. The horizontal error bars arise from the spatial variation in $\langle D_z \rangle_z$. The dashed line is the fitting curve $T_a = 0.41 H^2 / \langle D_z \rangle_z$.

3.6 Model application

Together with Xu and Nepf (2020), the present study provides a way to model vertical diffusivity within a canopy of emergent vegetation. This could be used to estimate the adaptation time-scale (Eqn. 13) and associated adaptation distance, which can be used to predict or interpret deposition patterns within marshes. The diffusivity can also be used within a RDM or a field-scale simulation tool (e.g., Delft-3D) to predict the fate of suspended sediment within a marsh. The model requires a characterization of the plant frontal area profile, $A(z)$ (e.g., see image analysis described in Figure 1 of Xu and Nepf 2020, and Figure 7), and the plant area density (m), culm diameter (d) and leaf width (w). These plant geometric parameters defined the vertical profiles of $a = mA$ and l_t (as in Eqn. 8). The vertical profile of velocity, $\langle \bar{u} \rangle$ can be inferred from Eqn. 11, or from the hydrodynamic simulation. Eqn. 9 estimates the turbulent kinetic energy, k_t . The diffusivity scale constants α_y and α_z are estimated from the solid volume fraction (Figure 2) and water depth (Eqn. 12). The vertical profile of vertical diffusivity, D_z , is then estimated from Eqn. 7. We note that, at the field scale the plant geometric parameters (A , m , d , and w) can vary in the horizontal

plane. Because velocity and turbulence adjust over fairly short distances (a few water depths) within emergent canopies (Figure 4 in Xu and Nepf 2020), the turbulent diffusivity (Eqn. 7) will also adjust quickly. This means that the model for turbulent diffusivity described in the present paper could be used to model spatial variation in diffusivity across scales of canopy variation, if the spatial distributions of A , m , d , and w are known.

4. Conclusion

The presence of vegetation alters the vertical structure of the mean and turbulent velocity, and these changes impact the vertical diffusivity and suspended sediment profiles. Compared to conditions without vegetation, but the same velocity, the vertically diffusivity within a *T. latifolia* canopy was both larger and exhibited a vertical variation correlated with plant morphology, both of which can be attributed to vegetation-generated turbulence. Specifically, vegetated-generated diffusivity was higher in the culm region near the bed, and decreased in the upper canopy, dominated by distributed leaves. Correlated to this, the SSC profile in the lower region of the canopy was nearly uniform, while in upper region the concentration decreased with distance from the bed. Drawing on existing models for stem-generated turbulence, a model for vertical diffusivity was validated with tracer data within cylinder arrays and then modified to reflect the specific morphology of the *T. latifolia* canopy. RDM simulations using the modified diffusivity model produced good agreement with the measured suspended sediment concentration. The new diffusivity model can be used to improve prediction of sediment fate in marsh systems.

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