Aquatic vegetation is a crucial part of wetland and floodplain ecosystems. It stabilizes river banks (Hackney et al., 2020), protects coasts from waves and storm surges (Barbier et al., 2011), and provides habitat for fisheries (Costanza et al., 1997). Wetlands sustain themselves partially through their ability to retain and accrete sediment. However, the influence of vegetation on water motion and sediment transport is complex. On the one hand, vegetation provides additional drag, which reduces current (Kouwen & Unny, 1973), facilitating sediment deposition (Abt et al., 1994) and increasing bed elevation. On the other hand, vegetation generates turbulence (Tanino & Nepf, 2008; Xu & Nepf, 2020), which can enhance erosion (Niño & Garcia, 1996), alter the vertical distribution of suspended sediment (Tseng & Tinoco, 2021), and decrease bed elevation in the vicinity of vegetation (Norris et al., 2021; Yagci et al., 2016). Recent studies have proposed ways to incorporate the impacts of vegetation on bedload transport by considering the related process of scour hole formation (Wu et al., 2021), or by modifying the parameters of the Einstein (1950) probabilistic model (Armanini & Cavedon, 2019). A deeper understanding of sediment transport within aquatic ecosystems is still critical (Fagherazzi et al., 2017) to facilitate wetland protection and restoration projects (Paola et al., 2011).
2. Background and Theory

This study considered the impact of vegetation on bedload transport, in which sediment maintains close contact with the bed. Most previous studies of bedload (e.g., Einstein, 1942; Engelund & Hansen, 1967; Meyer-Peter & Müller, 1948; Shields, 1936) relate sediment mass transport rate, \( q_s \), to the time-averaged bed shear stress, \( \tau \). For example, the Meyer-Peter–Müller (MPM) formula (Meyer-Peter & Müller, 1948) is a commonly used \( \tau \)-based model:

\[
q_s^* = 8\left(\theta - \theta_{cr}\right)^{1.5},
\]

in which \( q_s^* = q_s / \left( \rho_s w_d s_{50} \right) \) is the dimensionless sediment transport rate and \( \theta = \tau / \left[ \left( \rho_s / \rho \right) g s_{50} \right] \) is the dimensionless bed shear stress, with \( \tau \) the skin bed shear stress, \( \theta_{cr} \) the dimensionless critical shear stress, \( \rho_s \) the sediment density, \( \rho \) the fluid density, \( w_s \) the sediment settling velocity, \( g \) the gravitational acceleration, and \( s_{50} \) the median grain size of bed sediment.

Several studies have shown that turbulence contributes to the entrainment and mobility of individual grains (Celik et al., 2010; Shih & Diplas, 2018) as well as net sediment transport at the bed scale (Niño & Garcia, 1996; Salim et al., 2017; Sumer et al., 2003). Over a bare flat bed, the near-bed turbulent kinetic energy (TKE, \( k_i \)) is generated by bed shear and thus proportional to the bed shear stress (Soulsby, 1983), so that the impact of turbulence is implicitly embedded in the \( \tau \)-based sediment transport models. However, large roughness elements, including vegetation and bedforms, produce additional turbulence that also impacts sediment transport (Nelson et al., 1995; Yager & Schmeeckle, 2013; Yang & Nepf, 2018) but which is not captured by \( \tau \)-based models. Consequently, the \( \tau \)-based models significantly underestimate sediment transport in channels with obstacles (Nelson et al., 1995; Schmeeckle, 2015). Recent work has suggested that within regions of vegetation, turbulence is a better predictor than bed stress for incipient motion (Yang et al., 2016), resuspension (Liu et al., 2021; Tinoco & Coco, 2018), and bedload transport (Yang & Nepf, 2018, 2019). Therefore, we have recast the MPM formula in terms of TKE. Specifically, for the flat bare beds considered in MPM, bed stress is directly correlated with near-bed turbulence. We apply the conversion suggested by Soulsby (1983) based on flow measurements in atmospheric and marine boundary layers:

\[
k_i = 5.3 \tau / \rho,
\]

in which \( k_i \) is the near-bed TKE. Using this, we recast Equation 1 in terms of TKE,

\[
q_s^* = 0.66 \left( k_i^* - k_{i,cr}^* \right)^{1.5},
\]

in which \( k_i^* = k_i / \left[ \left( \rho_s / \rho - 1 \right) g s_{50} \right] = 5.3 \theta \) is the dimensionless TKE. Previous studies have shown that the critical TKE for sediment entrainment, \( k_{i,cr} \), is the same for vegetated and unvegetated channels (Liu et al., 2021; Yang et al., 2016). Based on this, we propose that \( k_{i,cr} \) can be estimated from previously determined critical bed shear stress for bare bed, that is, in dimensionless form, \( k_{i,cr}^* = 5.3 \theta_{cr} \) (based on Equation 2).

In application, Equation 3 uses the spatial-averaged turbulence \( \langle k_i \rangle \), which can be predicted within an emergent canopy of circular stems as a combination of bed-generated \( \langle k_{i,b} \rangle \) and vegetation-generated \( \langle k_{i,v} \rangle \) turbulence (Yang & Nepf, 2019; see Supporting Information S1 for model details). For canopy solid volume fraction (SVF) \( \phi < 0.1 \),

\[
\langle k_i \rangle = C_l U^2 \left[ 0.19 \kappa_{b,i} + \delta_{k_i} \left( \frac{2 C_{D,form} \theta}{\pi (1 - \phi)} \right)^{2/3} \right] \]

in which \( C_l \) is the bed drag coefficient, \( C_{D,form} \) is the stem form drag coefficient, and \( \delta_{k_i} \) is an O(1) scale constant. Equation 4 is valid if the velocity \( U \) is sufficient to produce stem turbulence, that is, stem Reynolds number \( Re_d = Ud / \nu > 120 \) (Liu & Nepf, 2016). A combination of Equations 3 and 4 predicts bedload based only on \( U \) and \( \phi \), which could be estimated from canopy biomass. The prediction has no dependence on stem diameter. This is somewhat surprising, because the stem diameter sets the scale of vegetation-generated
turbulence (King et al., 2012; Tanino & Nepf, 2008), and we expect larger eddies to be more effective in mobilizing sediment. The lack of dependence on stem size needs justification and testing, which is the main point of this study.

Bedload transport reflects the sum of individual grain dislodgement events (Niño & Garcia, 1996) and depends on the cumulative influence of hydrodynamic forces, set by both the magnitude and duration of the lift and drag interacting with the particle, which can be characterized by impulse (Diplas et al., 2008), work (Lee et al., 2012), or stream power (Shih & Diplas, 2018). These models suggest that larger eddies, which interact with a bed particle for a longer duration, are more effective in initiating particle motion during a single event. However, the number of stems producing eddies is also important. Consider two arrays of circular stems with the same SVF $\phi$, the same sediment $d_{50}$, exposed to the same channel-averaged velocity, $U$, and flow depth, $h$, but consisting of different stem diameter, $d$ (Figure 1). The array with larger $d$ has fewer stems (Figure 1a) and so produces larger but fewer eddies, compared to the array with smaller $d$ (Figure 1b). This trade-off between number (frequency) and size (duration) of turbulent interactions with the bed produces the same channel-averaged impulse in both channels, if turbulence intensity, which sets the force magnitude, is the same (Figure 1c). Within these constraints, we expect the same channel-averaged impulse and sediment transport rate, regardless of stem size. The present study used laboratory experiments to validate this conclusion. A more quantitative description of how the impulse model supports this conclusion is given in Supporting Information S1.

3. Methods

Laboratory experiments were conducted in a 1-m-wide and 10.4-m-long flume, with water and sediment recirculated separately. Velocity and sediment transport rate were measured for similar channel velocity and SVF, but different cylinder sizes ($d = 0.64, 2.5, \text{ or } 5.1 \text{ cm}$) and in both random and staggered emergent arrays (Table S1 for experimental conditions and Supporting Information S1 for photographs). Two randomly distributed arrays were constructed with mixed cylinder diameters ($d = 1.3 \text{ and } 1.9 \text{ cm}$, and $d = 1.3, 1.9, \text{ and } 5.1 \text{ cm}$). The random distributions were generated using the randperm() function in MATLAB to...
select the cylinder position. The number of cylinders per bed area was \( m = 0 \) to 775 m\(^{-2}\), corresponding to vegetation frontal area per volume \( a = md = 0 \) to 4.9 m\(^{-1}\) and \( \phi = \pi ad/4 = 0 \) to 0.049. These ranges were chosen based on marsh plants, mangrove pneumatophores, and young floodplain trees (Manners et al., 2015; Nepf, 2012; Norris et al., 2017). The 3-m-long array of cylinders occupied the entire channel width. A 9-cm layer of manually flattened sand (\( d_{so} = 0.6 \) mm, \( \rho_s = 2,650 \) kg/m\(^3\), see Supporting Information S1 for grain size distribution) was added within the array. The water depth was \( h = 12.0 \) ± 0.5 cm above the sand layer, measured with a ruler midlength along the array.

The sediment transport rate was measured 4 to 6 times every 4 hr using a butterfly valve to divert flow from the sediment recirculating pipe to a mesh bag (Figure S1). The collected sediment weighed at least 50 g and the duration of collection was at least 1 min, but no more than 30 min. The number of collections (4 to 6) was smaller when longer collection time was required, and a larger number was used when sediment transport showed considerable temporal variability. This was continued for up to 70 hr, until the measured sediment transport reached equilibrium, which was defined once the sediment transport rate of the last two measurement sets agreed within the standard error within each set, typically smaller than 10% of the mean value.

After the bed reached equilibrium, a Nortek Vectrino recorded instantaneous velocity components \( u(t) \), \( v(t) \), and \( w(t) \). Spherical glass beads (Potters Industries Inc. 110P8, median grain size \( d_{md} = 10 \) μm) were added to enhance the backscatter signal. At each position, a 150-s record was measured at 200 Hz. The sampling duration was confirmed by a convergence test of mean and turbulent flow statistics (Figure S2). For staggered arrays, the channel-averaged velocity, \( U \), was measured using a lateral transect at mid-depth and 2 m downstream from the array leading edge. A vertical profile was made at the point where the time-mean velocity matched the transect average. In a random array, two lateral transects provided an accurate estimate of \( U \) and \( \langle k_i \rangle \). Specifically, the velocity statistics converged to a constant value after averaging two complete transects chosen randomly along the array (see supporting information in Shan et al., 2020). Along each transect, two locations whose time-mean streamwise velocity and TKE were closest to the transect mean were selected for a vertical profile. The vertical profiles confirmed that mid-depth measurements reasonably represented near-bed flow conditions (Figure S3).

The velocity records were processed using the Goring and Nikora (2002) method to remove spikes, with the acceleration and velocity thresholds set to \( \lambda_2 = 1 \) and \( k = 1.5 \), respectively. After despiking, TKE was calculated at each position as \( k_i = \left( u^2 + v^2 + w^2 \right)/2 \), and its spatial average was denoted \( \langle k_i \rangle \). The integral time scale of turbulence, \( \Lambda_i \), was estimated using the autocorrelation function (Kundu et al., 2016):

\[
\Lambda_i = \int_0^{\infty} \frac{\langle v(t) v(t+\tau) \rangle}{\left[ v'(t) \right]^2} d\tau \approx \int_0^{\tau_l} \frac{\langle v(t) v(t+\tau) \rangle}{\left[ v'(t) \right]^2} d\tau
\]

(5)

in which \( \tau_l \) is the first zero crossing of the autocorrelation function. The lateral velocity, \( v(t) \), was used because the identification of the zero crossing was more precise, although similar values were obtained from the streamwise component. At each position, the local integral length scale was defined as \( l_i = \bar{u} \Lambda_i \), with \( \bar{u} \) the local time-averaged velocity. The spatial-averaged (across the transects) eddy length scale was denoted \( \langle l_i \rangle \).

4. Results

4.1. Bedload Sediment Transport

Considering a fivefold variation in stem diameter (0.64 to 2.5 cm), the measured bedload transport rate, \( q_w \), did not exhibit a dependence on the stem diameter, \( d \), but increased with spatial-averaged TKE \( k_i \) (Figure 2a). These results support the conclusion drawn from the impulse model, that is, sediment transport rate depended primarily on TKE and not stem size, such that \( q_w \) may be predicted from channel-averaged turbulence alone. Further, the arrays consisting of multiple stem diameters (downward triangles in Figure 2a) exhibited the same dependence on \( \langle k_i \rangle \) as the single-diameter arrays, indicating that the impulse description for single-diameter arrays (Figure 1) extends to arrays with multiple diameters.
4.2. Integral Length Scale

For arrays with mixed cylinder size, an average diameter \( d \) was defined that preserved the frontal area. This choice was made because turbulent eddies are expected to scale with the projected width of the plant elements, which has been confirmed for plants of real morphology (Xu & Nepf, 2020). Within a mixed array,
each stem diameter, \( d_i \), occurs at area density \( m_i \) (stems per bed area). The total frontal area per canopy volume is

\[
\langle a \rangle = \sum_{i=1}^{p} m_i d_i = \left( \sum_{i=1}^{p} m_i \right) \langle d \rangle,
\]

from which we define

\[
\langle d \rangle = \frac{\langle a \rangle}{\sum_{i=1}^{p} m_i} = \frac{\sum_{i=1}^{p} m_i d_i}{\sum_{i=1}^{p} m_i}.
\]

Within both staggered and random arrays of both uniform and mixed diameter, \( \langle l_c \rangle \) was proportional to \( \langle d \rangle \). Specifically, \( \langle l_c \rangle = (0.43 \pm 0.02) \langle d \rangle \) (Figure S4). This was consistent with Tanino and Nepf (2008, Figure 12, \( d = 0.6 \) cm), who also found \( l_c \) proportional to \( d \) within a sparse array (\( \Delta s/d > 2 \)). All cases in this study fell in the sparse array regime. Note that Tanino and Nepf (2008) measured a larger scale coefficient, \( l_c/d = 1 \), which might be attributed to the smaller Reynolds numbers in that study (\( Re_d < 600 \), vs. \( Re_d \geq 1000 \) in this study).

### 4.3. Turbulence

Although the turbulence arises from stem wakes at a scale proportional to \( d \), Equation 4 does not include the stem diameter, \( d \). This is due to the cylindrical geometry of the plant model, such that the same vegetation length scale \( (d) \) determines both the scale of turbulence, \( l_c \sim d \), and the SVF \( \phi = (\pi/4) m d^2 \) (see details in Tanino & Nepf, 2008). To accommodate canopies of mixed element scale, we follow Xu and Nepf (2020), who predicted depth-averaged TKE using the depth-averaged values of \( a \) and \( l_c \). It is reasonable to expect that a similar spatial average can be used in the horizontal plane to accommodate variations in stem diameter and to make the substitution \( \langle l_c \rangle \sim \langle d \rangle \), as shown in Section 4.2, such that the spatial-averaged TKE within heterogeneous arrays can be described from \( \langle a \rangle \) and \( \langle d \rangle \):

\[
\langle k_s \rangle = C_i U^2 \left[ \frac{0.19}{k_{i,b}} + \delta_{k_i} \left[ \frac{C_{D, form} \langle a \rangle \langle d \rangle}{2 (1 - \phi)} \right]^{2/3} \frac{k_{i,v}}{k_{i,b}} \right]^{2/3} U^2
\]

(8)

For \( Re_d \geq 200 \), Etminan et al. (2018) showed that \( C_{D, form} \approx 0.9 \ C_D \), with \( C_D \) the total drag coefficient, which can be predicted following Etminan et al. (2017):

\[
C_D = \left[ \frac{1 - \phi}{1 - \sqrt{2 \phi / \pi}} \right]^{2} \left[ 1 + 10Re_d^{2/3} \left( \frac{1 - \phi}{1 - \sqrt{2 \phi / \pi}} \right)^{-2/3} \right].
\]

(9)

A least squares fit of Equation 8 with measured \( \langle k_s \rangle \) yielded \( \delta_{k_i} = 0.52 \pm 0.07 \) (95% CI, Figure S5). When a canopy consists of a single diameter, Equation 10 is equivalent to Equation 4. Given this, the scale constant for Equation 8 was consistent with Yang and Nepf (2019), who found \( \delta_{k_i} = 0.4 \pm 0.3 \) (95% CI) for an array with a single diameter (\( d = 0.6 \) cm).

### 5. Discussion

#### 5.1. Comparison of Stress-Based and Turbulence-Based Predictions of \( q_s \)

Measurements from previous studies were combined with the present study to both contrast the predictive capability of bed stress and TKE within vegetated regions and to validate the prediction of bedload transport using Equations 3 and 10. For each case, including the present study, the bed stress and TKE were predicted from measured channel-averaged velocity and array characteristics (details in S1). The bed shear stress was predicted using Equation 6 in Yang and Nepf (2018):
which reflects the reduction of the viscous sublayer due to vegetation-generated turbulence.

First, the measured bedload transport rate (symbols in Figures 2b and 2c) had only a weak dependence on bed stress (Figure 2b), with \( q_s^* \) varying by up to 2 orders of magnitude for conditions with the same \( \theta \). In contrast, \( q_s^* \) collapsed into a clear monotonic trend when plotted versus \( k_{t,cr}^* \) (Figure 2c). This demonstrated that bedload transport in vegetated channels was better described as a function of TKE, which echoes Figure 3 in Yang and Nepf (2018; also see Supporting Information S1). However, this study extended the result to arrays of different stem diameter (\( d = 0.6 \) to 5.1 cm) and to arrays of mixed stem sizes.

Second, this study considered the MPM model, which includes a threshold for sediment motion. This is in contrast to Yang and Nepf (2018), who used the Einstein (1942, 1950) model (Supporting Information S1), which describes bedload as the sum of individual grain dislodgement events related to a probabilistic distribution, for which a threshold of sediment motion is not defined. However, for the time scale of interest in typical experiments, \( 10^6 \) to \( 10^7 \) min, and for many applications of monitoring and predicting bed evolution, \( 10^0 \) to \( 10^1 \) hr, a critical threshold makes physical and practical sense.

The MPM model (Equation 1) was recast in terms of TKE (Equation 3), which required a prediction of \( k_{t,cr}^* \). Previous studies have shown that the threshold for grain motion can be described in terms of TKE and that \( k_{t,cr}^* \) is the same for vegetated and unvegetated channels with the same bed sediment (Liu et al., 2021; Tinoco & Coco, 2018; Yang et al., 2016). Hence, we proposed that the threshold of sediment motion documented for bare beds in terms of \( \theta^{*} \) can be used to estimate the turbulence threshold, \( k_{t,cr}^* = 5.3 \theta^{*} \), using Equation 2.

For the included studies, \( d_{50} = 0.5, 0.6, \) and 0.93 mm, for which \( \theta^{*} = 0.03 \) was estimated from the Shields diagram, using the fitted curve in Soulsby (1997). The corresponding \( k_{t,cr}^* = 0.16 \). The red dashed curves in Figure 2 correspond to these critical values. We note that measurements of incipient motion exhibit significant spread, which has been attributed to factors including bed characteristics (Lamb et al., 2008) and the different definitions for incipient motion (Buffington & Montgomery, 1997). From the spread in the Shields diagram, but considering only unidirectional flow conditions (e.g., Buffington & Montgomery, 1997; Soulsby, 1997; Whitehouse et al., 2000), we extracted a minimum (\( \theta_{cr} = 0.02 \)) and a maximum (\( \theta_{cr} = 0.04 \)), corresponding to \( k_{t,cr}^* = 0.11 \) and 0.21, respectively. These values were used to define the green shaded region in Figures 2b and 2c, respectively. Note that Yang et al. (2016) used visual observation to determine \( k_{t,cr}^* = 0.15 \) for grain size \( d = 0.6–0.85 \) mm within arrays of different \( \theta \) (Figure 3 in Yang et al., 2016). This corresponded to \( \theta_{cr} = 0.028 \), consistent with the range of critical shear stress extracted from the Shields diagram. This agreement supports the proposal that \( k_{t,cr}^* \) can be estimated from archived measurements of \( \theta_{cr} \).

Finally, the stress-based MPM formula did poorly predicting sediment transport within model vegetation (Figure 2b), underpredicting the measured transport rate by up to 3 orders of magnitude. In contrast, when MPM was recast in terms of TKE, using \( k_{t,cr}^* = 5.3 \theta_{cr} \), the prediction matched the measurement more closely, with only a factor-four maximum deviation from the measurement.

**5.2. Model Limitations**

The equations for predicting bedload transport (Equations 3, 4, and 8) have some limitations. First, bed-generated turbulence is characterized by \( C_f \) defined by a logarithmic profile over an unvegetated bed. Within a canopy, the velocity profile is more uniform, and the bed shear stress may be elevated due to thinning of the viscous sublayer by vegetation turbulence (Etminan et al., 2018; Yang et al., 2015). In addition, bed-generated turbulence can be broken down by stems, shifting turbulent energy from depth-scale (bed turbulence) to the stem-scale \( I_s \), making it difficult to strictly partition bed and vegetation contributions. Despite these issues, Equations 4 and 8 performed well in predicting canopy turbulence, in part because the vegetation-generated turbulence is often the dominant term. Specifically, laboratory experiments (Yang & Nepf, 2019, Figure 4b) and numerical simulation (Etminan et al., 2018, Figure 11) indicate that bed-generated turbulence is small compared to vegetation-generated turbulence for \( \phi > 0.01 \), making weaknesses
in $k_{t,v}$ prediction unimportant. Second, the model assumes $l_{p} \sim d$, which is valid for $\phi < 0.1$ and 0.06 for a regular and random array, respectively (Tanino & Nepf, 2008). For $\phi \geq 0.1$, the turbulence length scale is constrained by stem spacing, that is, $l_{p} \sim \Delta x$, which modifies the form of Equation 4 (Tanino & Nepf, 2008). Third, the model assumes an emergent canopy. If the canopy is submerged, turbulence may be additionally generated in the shear layer at the canopy top (e.g., Zhang et al., 2020). Canopy-scale turbulence forms when the nondimensional meadow density $ah_{c} > 0.1$, with $h_{c}$ the canopy height (Nepf, 2012). If the canopy is not too dense ($ah_{c} \leq 0.5$), this turbulence may reach the bed and influence sediment transport (e.g., Figure 3 in Luhar et al., 2008), a process that is not represented in the present model. Finally, grain-to-grain interaction can also influence sediment transport, including grain arrangement (Masteller & Finnegan, 2017) and collective grain entrainment (Lee & Jerolmack, 2018). These factors were not considered within the model, and the obstruction provided by the vegetation may alter these affects from those observed in bare channels.

### 5.3. Extension to More Complex Plant Morphology

Vegetation density is often characterized in terms of biomass $B = \rho_{s} \phi h_{c}$ (mass/bed area), which is directly related to SVF ($\phi$), with $\rho_{s}$ the plant material density. Therefore, it is useful to consider a prediction of TKE and bedload using $B$ to infer $\phi$. As an example, we considered two plant species with different morphology (Supporting Information S1), *Typha latifolia* (with branching leaves emerging from a short cylindrical culm) and *Rotala indica* (with decussate leaves distributed along the stem in orthogonal pairs). Even for these complex morphologies, $l_{p}$ scales with the characteristic width of plant element, $d$, following the morphological variation over depth (Figure 12 in Xu & Nepf, 2020). Therefore, we retain the assumption in Equations 4 and 8 that the canopy-averaged turbulence scale is proportional to the canopy average plant element width, that is, $\langle l_{p} \rangle = \langle d \rangle$.

For a canopy of cylindrical stems, $\phi = (\pi/4)ad$, which makes Equations 4 and 8 equivalent. However, for real plant morphology with flat elements like leaves, $\phi < (\pi/4)ad$, so that Equation 4 will underpredict turbulence, compared to Equation 8. Specifically, $\phi\{[\pi/4]a/(\phi)(d)\} = 0.24 \pm 0.02$ (*Typha*, SE) and $0.30 \pm 0.01$ (*Rotala*, SE), compared to $\phi[\{\pi/4\}(a)/(\phi)(d)] = 1$ for cylinders. Conveniently, this morphology ratio is not a function of water depth (Figure 3a). This was expected for *Rotala*, which has a vertically uniform frontal area (Figure 1f in Xu & Nepf, 2020). In contrast, *Typha* has a nonuniform frontal area. However, its characteristic width $d$ varies in a complementary trend with $a$ (Figure 3b), such that the product $ad$ has little vertical variation.

Xu and Nepf (2020) validated Equation 8 for the prediction of TKE within canopies of *Typha* and *Rotala* (repeated in Figure 3c). Here, we considered a modification of Equation 8 cast in terms of $\phi$, derived using the morphology ratio (Figure 3a). The plant-specific morphology ratio $\phi\{[\pi/4]a/(\phi)(d)\}$ was used to replace $\langle a \rangle /\langle d \rangle$ in Equation 8, and the constants incorporated into a prefactor $\delta_{k_{t,v}}$ (2.6 ± 0.2 for *Typha* and 2.2 ± 0.1 for *Rotala*) in $k_{t,v}$:

$$\langle k_{t} \rangle = \frac{C_{U}^{2}}{0.19} + \delta_{k_{t,v}} \left[ \frac{2C_{D,form} \phi}{\pi (1 - \phi)} \right]^{2/3} U^{2}$$  \hspace{1cm} (11)

Within the *Typha* and *Rotala* canopies, the bed contribution $k_{t,b}/U^{2} = 0.019 \pm 0.002$ (SE) was estimated from bare-bed measurements, and measured $C_{D} = 1.62 \pm 0.11$ for *Typha* and $C_{D} = 1.75 \pm 0.15$ for *Rotala* (SE), all reported in Xu and Nepf (2020, Figure 5b). The $\langle k_{t} \rangle$ predicted by Equation 11 agreed with the measured $\langle k_{t} \rangle$ to within factor 3 (Figure 3d). To apply this in the field, one could use measurements of biomass ($B$) to estimate SVF, $\phi = B/(\rho_{s} h_{c})$.

### 6. Conclusions

In canopies of different stem sizes and of mixed stem sizes, bedload transport rate was a function of TKE alone, with no dependence on stem size or distribution. This was consistent with the impulse model, which describes sediment entrainment as a function of both the duration and magnitude of turbulent events.
Specifically, canopies of comparable SVF and velocity (producing the same TKE magnitude) but different stem sizes produce similar impulse, due to a trade-off between number (frequency) and size (duration) of turbulent interactions with the bed. Based on this, indirect methods for predicting turbulence (e.g., through measured or predicted energy gradients) may be used to predict sediment transport, without requiring specific descriptions of plant morphology. Further, the Meyer-Peter–Müller bedload equation was recast in terms of TKE, with critical TKE inferred from the Shields diagram. By accounting for the morphology-dependent ratios of nondimensional frontal area $\frac{a}{d}$ and SVF, one can predict TKE and thus sediment transport from biomass, flow depth, and flow velocity. This represents an important step in the description of turbulence and bedload transport within vegetated regions, enabling prediction of coastal and riverbank evolution.

**Data Availability Statement**

Data presented in this paper are available on Figshare: [https://doi.org/10.6084/m9.figshare.15027069](https://doi.org/10.6084/m9.figshare.15027069) and [https://doi.org/10.6084/m9.figshare.12228812.v2](https://doi.org/10.6084/m9.figshare.12228812.v2).
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