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Key Points:

- Weak and moderate bed-load transport in vegetated flows is considered as live-bed pier scour in multiple stems aligned in tandem
- The patch-averaged bed-load transport rate is estimated from the bed-load fluxes in the scour holes around vegetation stems
- The flow intensity and transport rate are parametrized using the vegetation density and stem size to characterize the spatial variability

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Bed-Load Transport in Vegetated Flows: Phenomena, Parametrization, and Prediction

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Abstract This study presents an experimental study on bed-load transport in the presence of emergent vegetation, which is simulated using uniformly sized circular cylinders arranged in a homogeneous distribution. The spatial variability of bed-load fluxes in vegetated flows is first examined. Then a model is proposed for evaluating the bed-load transport rate based on the scour holes that form around the vegetation stems. The influences of spatial variability and intensified turbulence on sediment transport are finally considered by relating the dimensionless transport rate and flow intensity to the stem size and vegetation density. The derived formula for predicting the bed-load transport rate in vegetated flows is applicable for weak to moderate transport conditions.

1. Introduction

Wetland projects such as dredging management, erosion protection, and restoration of aquatic organism habitats require evaluation of the sediment transport rate in flows with vegetation (Canter, 2018; Lowe & Ghisalberti, 2016). The transport rate in a vegetated flow, however, is hard to be accurately predicted because of the vegetation-water-sediment interactions. As a result, few works have hitherto been conducted, particularly on bed-load transport, in vegetated flows (López & García, 1998; Nepf, 2012). Bed-load transport is controlled by the near-bed turbulence, which is highly three-dimensional around the vegetation stems (D. Liu et al., 2008; Stoesser et al., 2010). Additionally, bed morphology also interacts with the turbulence induced by vegetation, making the prediction of bed-load transport rate even more difficult.

Experimental studies on bed-load transport in vegetated flows were usually conducted in flumes with emergent rigid vegetation, which were simulated by using circular cylinders with uniform size and homogeneous distribution. Tang et al. (2013) investigated the incipient motion in flows with aligned arrays of vegetation stems through visual observation. Yang et al. (2016, 2016b) further studied the incipient motion of vegetation with staggered arrangement using high-speed videos. Yager and Schmeeckle (2013) also used high-speed videos to deduce the bed-load transport rates and spatial distribution of the sediment fluxes. Being constrained by the measuring methods, the data collected by these early studies are subject to high uncertainties. More recently, Yang and Nepf (2018) used a flume with a sediment recirculation system and allow the longitudinal slope of the sand bed to self-adjust. After the sediment transport has reached the equilibrium, a uniform flow was obtained in the flume, which enabled the measurement of a steady transport rate. Armanini and Cavedon (2019) conducted experiments in a similar flume but measured the flow velocities for different vegetation densities but the same transport rates. They placed different vegetation models end-to-end in a flume and waited for the bed-load transport in every vegetation patch to reach equilibrium before measurement. These experiments were more accurate but time-consuming for measuring relatively low transport rates because, in this case, the bed slope is hardly changed by erosion or deposition. In the present study, flume tests with a mobile sand bed and a sediment trap were conducted. Furthermore, with the help of a slope-adjustable flume and precise control of the elevation of the sand-bed surface before scouring, weak and moderate bed-load transport rates were measured with high accuracy. Accordingly, the relation between the transport rates and spatially averaged (bulk) flow velocities can be more precisely presented.

Yager and Schmeeckle (2013) reported that for the same bulk flow velocity, the bed-load transport rate in a vegetated patch is significantly higher than that in non-vegetated flows, and the patch-averaged transport rates are also different for various vegetation distributions. To obtain a unified formula of bed-load transport

rate in vegetated flows, most researchers introduced a parameter to describe the density of the vegetation distribution, commonly defined as the bed areal occupancy or vegetation density ϕ (Nepf, 1999). An earlier attempt (Tang et al., 2013) modified an empirical formula for non-vegetated flows, which was proposed by Zhang et al. (1998), to predict the incipient motion in vegetated flows by using the bulk flow velocity and vegetation density. On the other hand, other studies had tried to find a hydrodynamic parameter to predict the transport rate regardless of the differences in vegetation densities. For the same spatially averaged shear stress, Yager and Schmeeckle (2013) claimed that the bed-load transport rates for different vegetation densities are in the same order of magnitude.

These early approaches still cannot be used to predict the bed-load transport rate readily. In order to obtain a practical formula for the prediction, later studies proposed the use of a deterministic hydrodynamic parameter that can be calculated from the vegetation density explicitly (Yang & Nepf, 2018). Yager and Schmeeckle (2013) elucidated that the near-bed turbulence intensities increased by vegetation stems held the key influence in enhancing bed-load transport. Thus, Yang and Nepf (2018) measured the spatially averaged near-bed turbulent kinetic energy (TKE) and reported that it could be the deterministic parameter for predicting the bed-load transport rate. Moreover, they estimated the average near-bed TKE through a combination of the vegetation-induced TKE and the bed-induced TKE (proposed by Yang et al., 2016b). Otherwise, Armanini and Cavedon (2019) modified Einstein's bed-load formula to predict the transport rate by considering the patch-averaged bed resistance as the deterministic parameter. The bed resistance was calculated by subtracting the drag on vegetation stems from the total flow resistance, which also can be estimated with the vegetation density.

Notwithstanding these advancements, published studies still have not reached a consensus on the deterministic parameter for predicting the bed-load transport rate in vegetated flows. This is due to several limitations of these studies. First, the stem-scale mechanism of the intensified patch-averaged bed-load transport is still uncertain. For instance, Yager and Schmeeckle (2013) considered that it is related to the enhanced localized erosion where the flow is obstructed by vegetation stems, which act like bridge piers. However, Armanini and Cavedon (2019) argued that the increased shear stress on the unobstructed portion of the bed in a vegetation patch is the primary reason. Second, the amount of relevant measurements is still limited. The similar experimental studies presented in recent years (Armanini & Cavedon, 2019; Yager & Schmeeckle, 2013; Yang & Nepf, 2018) kept the vegetation stem size constant in their own experiments and varied the vegetation density by merely changing the distributions of the stems. They showed that their formulas were applicable to all the data including those from other studies, but there are still some consistent biases between the data from different sources. This could be associated with systematic errors caused by different measurement methods used in different studies. Third, Yager and Schmeeckle (2013) pointed out that the spatial variabilities of the flow and sediment fluxes have to be investigated because they are the key factors to determine the bed-load transport rate. Nonetheless, some previous researchers (Yager & Schmeeckle, 2013; Yang & Nepf, 2018) had not considered the spatial distribution of the near-bed turbulent flow or the sediment fluxes but only applied their patch-averaged values.

To overcome the above limitations, two different sizes of vegetation were used in the same experimental setup. Additionally, the bed-load transport rates were measured with higher accuracy, and the top-view images of the bed areas with sediment exchange and the bed forms were captured. According to the observed phenomena of sediment mobility shown by the captured bed images, it is deduced that the spatial variability of the bed-load fluxes around vegetation stems is closely related to the live-bed scour around rows of aligned stems. As suggested by the numerical simulations of the flow and bed morphology in patches of uniformly distributed stems done by Kim et al. (2015), if the stem-scale sediment motion is described precisely, the patch-scale transport rate through an infinitely long vegetation patch can be evaluated.

To simplify the influence of the spatial variability on evaluating bed-load transport rate, some assumptions are proposed for the weak and moderate bed-load transport through sparse vegetation. Based on these assumptions, a sediment-motion model is derived, in which the patch-averaged transport rate only depends on sediment exchange in the scour hole around an individual stem. According to this model, two dimensionless parameters are proposed: the first representing the intensity of bed-load transport from the scour holes through a transverse cross section and the second describing the intensity of the near-bed turbulent flow around a vegetation stem. By analyzing the bed-load transport data with different sizes of sediments

Figure 1. Side view of the slope-adjustable flume with the sediment trap and vegetation model (flow from right to left).

and vegetation stems, which are compiled from the present and published studies, it is found that not only the vegetation density but also the vegetation stem size should be included in the hydrodynamic parameter. Finally, an empirical formula is proposed to predict the weak and moderate bed-load transport rate in channels with sparse vegetation.

2. Methods

2.1. Experimental Setup

Figure 1 shows the experimental setup which is a slope-adjustable flume (12 m long, 0.6 m wide, and 0.6 m deep) with a 0.5 m long rectangular sediment trap that was located at a distance 3.5 m upstream from the flume exit. The bottom of the sediment trap had a cone shape so that the trapped sediments could be collected through a tube beneath the cone. An 8 m section, which extended from the flume entrance to the upstream end of the sediment trap, was covered by a 10 cm thick layer of quartz sand (density of the sand $\rho_s = 2,648 \text{ kg/m}^3$) with a uniform grain size distribution. The sediment has a median diameter $D = D_{50} = 0.931 \text{ mm}$, which is the minimum chord of the particle projection, measured with a CAMSIZER[®] optical particle sizer, and the standard deviation $\approx D_{84}/D_{16} = 1.61$. The model vegetation was placed immediately upstream of the slope entrance. The vegetation was simulated by arrays of glass-fiber circular cylinders with a homogeneous staggered arrangement (see Figure 2a), which is similar to the arrangements used in previous studies (Armanini & Cavedon, 2019; Cheng & Nguyen, 2011).

To ensure that the slope of the bed was uniform and could be controlled by the tilting flume, the sand layer was first flattened to have a uniform elevation before the discharge was applied. Then, the cylinders, which were used to simulate vegetation stems, were vertically inserted into the sand bed after the bed was flattened. To ascertain the exact position and verticality of the cylinders, they were fixed to two layers of plastic sheets on the top (see Figures 2b and 2c). The plastic sheets were 1 m long and 0.5 m wide, with staggered arrays of pre-drilled holes. The cylinders were 1 m in length, thereby being long enough not to be submerged in the flows. Finally, five pieces of sheets-cylinders-assembled vegetation models (see Figure 2) were placed end to end in the flume and inserted into the sand bed to form a 5-m long section covered with evenly distributed vegetation stems. The last row of stems was placed immediately upstream of the slope entrance of the sediment trap. The thickness of the sand bed extended to the upstream entrance of the flume (see Figure 1).

Figure 2. Schematic of the sheets-cylinders-assembled vegetation model: (a) top view; (b) side view; (c) isometric view.

Adopting the above procedures in preparing the sand bed, the difference in the bed elevations was controlled to within ± 1 mm (measured by using a point gauge with a 1-mm accuracy), and the thickness of the sand layer was set at 10.0 cm, which was thick enough to allow for the full development of bed morphology. Consequently, the present experiment can be conducted through directly adjusting the bed slope by tilting the flume slope instead of waiting for it to self-adjust, as was done by previous researchers (Armanini & Cavedon, 2019; Yang & Nepf, 2018), making it more efficient for measuring very weak bed-load transport rates.

2.2. Procedures for Measuring Bed-Load Transport Rates

The flow depth h was always kept at 30 cm by adjusting the tailgate. To measure the bed-load transport rates from extremely weak to moderate state, the discharge rates from small to large were applied correspondingly in continuous tests. In each test, a target discharge rate was first reached by increasing the pump frequency. Then, the slope and tailgate of the flume were adjusted iteratively to obtain a uniform flow condition. After a sufficient duration (more than 30 min) for the flow and bed forms to become steady, a uniform flow was obtained by ensuring the same flow depths at the locations immediately upstream and downstream of the vegetated section, which were respectively measured using two point gauges with an accuracy of ± 2 mm (see Figure 1). The waiting time before reaching equilibrium was measured for every case of vegetation densities when the sediment transport was the weakest. The transport rates were continuously measured every 5 min from the beginning, and the time before the measurements started fluctuating around a constant value steadily was recorded. For the different vegetation densities, the duration before the weakest bed-load transport to reach equilibrium was at most 30 min. Thus, the 30-min duration was also sufficient for other tests with higher transport rates to reach equilibrium.

Theoretically, erosion at the upstream end of the vegetated section is more intense (Liu & Nepf, 2016). However, in the present study, the vegetated section was long enough that the scour at the entrance to the vegetation patch did not affect that at the exit, and the duration of each test was not that long to cause significant changes in the bed slope. Thus, once the bed morphology had become steady, the sediment motion at the downstream end of the vegetation section could be considered as in a quasi-equilibrium condition. The transport rate measured with the sediment trap can represent the patch-averaged transport rate in an infinitely large vegetation patch because the finite vegetation section in the present experiment was wide and long enough.

The discharge rate was simultaneously measured with the flow meter installed on the pipe (see Figure 1) while the bed-load transport rate was being measured. The sand in the sediment trap was collected intermittently during a test at the same intervals. The sampling time was between 5 and 60 min depending on the intensity of bed-load transport. The total sediment-collection time for each test always exceeded 30 min to reduce measurement errors.

However, because the trapped sediment was not continuously re-circulated in the flume, two factors may contribute to gradually reducing the transport rates due to scouring. First, for a relatively intense bed-load transport, the bed elevation in the upstream patch kept decreasing, which may affect the flow due to the changed bed slope. Liu & Nepf (2016) stated that the vegetation-patch-scale erosion starts from the upstream section. To minimize such effects, the amount of sediment collected was limited. Considering that if 2 kg of sediment (whose bulk density is assumed as 1.5 g/cm^3) were eroded from the 1-m most upstream part of the vegetation section, the bed elevation would have reduced 2.22 mm, which was near the admissible measurement errors of the two point gauges (± 2 mm) that were used to monitor the water-surface slope. Given this estimate, the amount of sediment collected in each run was limited to 2 kg.

Second, for a weak transport, although the variation in the bed elevation was insignificant, the upstream sediment supply may become another issue because sediment around the stems at the most upstream end was scoured under the clear-water condition. As the sediment transport was weak, the scour holes would stop developing and cease to provide bed-load sediment downstream once the bed forms reached equilibrium. To examine this potential setback, the lowest transport rates for all cases were measured hourly, and a perceptible decreasing trend of transport rates was merely observed after 5 h. Therefore, the running time

of each test was limited to 5 h, or the decrease of upstream sediment supply could affect the transport rate at the entrance of the sediment trap.

Consequently, in a run with a constant flow rate, the trapped sediment was collected multiple times before their total mass exceeded 2 kg or the running time exceeded 5 h. Finally, the sediment samples were weighed and averaged to calculate the transport rate, before being poured back evenly to the upstream patch for preparing the execution of the next test. By this means, the sediment was re-circulated intermittently while ensuring that the influence on the steady transport rates was negligible at all times.

2.3. Experimental Conditions and Data

Laboratory tests of the non-vegetated flow and six cases with different vegetation densities and sizes were carried out. The experimental conditions and the measured bed-load transport rates are presented in Tables 1 and 2. Two types of vegetation stems with diameters $d = 7.8$ and 10.0 mm were tested in this study. All the vegetation stems were distributed in the same staggered arrangement, but the intervals between the two nearest aligned stems were different from case to case. The longitudinal interval L_x and transverse interval L_y (see Figure 2a) between the two nearest aligned stems were equal and set as 6, 9, and 12 cm in each case for the same stem size. The vegetation density is the spatial occupancy of emergent vegetation,

$$\phi = \frac{\pi d^2}{2L_x L_y} \quad (1)$$

In this study, ϕ was in the range from 0.66% to 4.36%, which corresponded to a sparse vegetation distribution as suggested by Nepf (2012b).

Moreover, the stem Reynolds number is defined as

$$\text{Re}_d = \frac{U_v d}{\nu} \quad (2)$$

In which ν is the kinematic viscosity and U_v is the bulk flow velocity in vegetated flow that is calculated using

$$U_v = \frac{1}{(1 - \phi)} \frac{q}{h} \quad (3)$$

where q is the discharge rate per unit width, and h is the flow depth. For the range of flow intensities applied in the present experiments, Re_d varied from 1,500 to 3,500. Tanino and Nepf (2008b) claimed that when $\text{Re}_d > 120$ for the sparse distribution ($2d / (L_x^2 + L_y^2)^{1/2} < 0.56$), the turbulent flow in emergent vegetation was well developed, and hence the spatial average of vegetation-induced TKE, k_v , could be estimated by using

$$k_v \approx 1.2 \left(C_{Dv} \frac{\phi}{(1 - \phi)\pi / 2} \right)^{2/3} U_v^2 \quad (4)$$

in which C_{Dv} is the average stem drag coefficient (Tanino & Nepf, 2008a). Here, C_{Dv} is used to approximate the form (or pressure) drag coefficient and k_v is approximately calculated through the formula for evaluating TKE induced by form drag, because the friction drag is far less than the form drag and can be omitted when turbulence is well developed (Etminan et al., 2018).

2.4. Observations of Particle Mobility

Sediment mobility on the bed in a vegetated flow varies spatially, which is not the same as that in a non-vegetated flow over a plane sand bed. Einstein (1950) stated that sediment exchange is the key factor in determining bed-load transport rates. Therefore, the location where sediment exchange is active on the bed in

Table 1
Experimental Data and Conditions^{a,b,c}

Case	d	L_y	Φ	slope i	U_v	q_B	$\sigma(q_B)$	$T_B(N_B)$	Comparison of measured transport rate
No.	m	m	%	1:1,000	m/s	m ² /s	m ² /s	min	
Non-vegetated flows									
0.1	0	∞	0.00	0.0	0.358	1.33E-08	3.81E-09	80(4)	
0.2	0	∞	0.00	0.0	0.361	2.36E-08	2.88E-09	60(3)	
0.3	0	∞	0.00	0.0	0.370	3.79E-08	3.40E-09	60(6)	
0.4	0	∞	0.00	0.0	0.380	6.16E-08	7.66E-09	60(6)	
Vegetated flows									
1.1	7.8	0.12	0.66	3.3	0.229	2.26E-08	8.82E-10	180(3)	>Figure 5a, $\approx$ Figure 8a
1.2	7.8	0.12	0.66	3.6	0.239	5.96E-08	1.56E-09	120(3)	
1.3	7.8	0.12	0.66	3.9	0.251	2.78E-07	2.01E-08	180(6)	$\approx$ Figure 5b
1.4	7.8	0.12	0.66	4.2	0.263	5.02E-07	2.34E-08	60(6)	
1.5	7.8	0.12	0.66	4.5	0.273	9.03E-07	8.64E-08	30(6)	
1.6	7.8	0.12	0.66	4.8	0.284	1.28E-06	2.19E-07	30(6)	<Figure 5c
2.1	10	0.12	1.09	3.4	0.202	1.25E-08	1.71E-09	240(3)	
2.2	10	0.12	1.09	4.1	0.220	7.29E-08	4.08E-09	90(3)	
2.3	10	0.12	1.09	4.8	0.237	2.65E-07	1.88E-08	100(5)	
2.4	10	0.12	1.09	5.4	0.251	6.01E-07	6.77E-08	60(6)	
2.5	10	0.12	1.09	6.1	0.268	1.38E-06	7.90E-08	30(6)	
3.1	7.8	0.09	1.18	4.5	0.187	2.56E-09	2.62E-10	150(5)	
3.2	7.8	0.09	1.18	4.6	0.193	4.86E-09	7.14E-11	90(3)	
3.3	7.8	0.09	1.18	4.8	0.196	1.40E-08	4.35E-10	60(2)	
3.4	7.8	0.09	1.18	5.0	0.203	2.17E-08	1.71E-09	120(4)	
3.5	7.8	0.09	1.18	5.0	0.208	3.64E-08	1.90E-09	120(6)	
3.6	7.8	0.09	1.18	5.0	0.212	5.34E-08	2.71E-09	120(6)	
3.7	7.8	0.09	1.18	5.5	0.216	9.84E-08	7.34E-09	60(6)	
3.8	7.8	0.09	1.18	5.7	0.222	2.06E-07	8.32E-09	60(6)	
3.9	7.8	0.09	1.18	5.8	0.227	2.67E-07	2.17E-08	60(6)	
3.10	7.8	0.09	1.18	6.1	0.232	4.46E-07	5.33E-08	60(6)	
4.1	10	0.09	1.94	3.9	0.165	6.34E-09	8.65E-12	120(2)	
4.2	10	0.09	1.94	4.0	0.171	9.67E-09	1.09E-09	120(2)	
4.3	10	0.09	1.94	4.2	0.177	2.09E-08	3.67E-09	120(2)	
4.4	10	0.09	1.94	4.4	0.183	3.21E-08	4.62E-09	90(3)	
4.5	10	0.09	1.94	4.6	0.187	3.82E-08	1.37E-09	90(3)	
4.6	10	0.09	1.94	5.0	0.192	6.17E-08	3.56E-09	60(3)	
4.7	10	0.09	1.94	5.5	0.200	1.12E-07	9.94E-09	60(3)	
4.8	10	0.09	1.94	5.9	0.205	1.58E-07	9.05E-09	60(6)	
4.9	10	0.09	1.94	6.3	0.211	2.41E-07	1.06E-08	60(6)	
4.10	10	0.09	1.94	6.7	0.216	3.43E-07	2.94E-08	60(6)	
4.11	10	0.09	1.94	7.0	0.221	5.12E-07	3.94E-08	60(6)	<Figure 7a

^aThis table is continued by Table 2. ^b σ , T_B , and N_B are standard deviation, total running time, and sampling numbers of the bed-load transport rate measurements.

^cFigure reference is given for the specific measurement case to which the sediment transport is most closely comparable. The signs denote that the measured transport rate is higher (>)/lower (<) than, or close to ($\approx$) the transport rate for the case in the figure.

Table 2
Experimental Data and Conditions (Continued)

Case No.	D m	L_y m	ϕ %	Slope i 1:1,000	U_v $\text{m}\cdot\text{s}^{-1}$	q_B $\text{m}^2\cdot\text{s}^{-1}$	σ $\text{m}^2\cdot\text{s}^{-1}$	$T_B(N_B)$ min	Comparison of measured transport rate
5.1	7.8	0.06	2.65	7.5	0.159	3.68E-09	N.A.	60(1)	
5.2	7.8	0.06	2.65	8.0	0.164	5.90E-09	N.A.	60(1)	
5.3	7.8	0.06	2.65	7.5	0.167	1.23E-08	N.A.	60(1)	
5.4	7.8	0.06	2.65	8.0	0.168	1.25E-08	N.A.	60(1)	
5.5	7.8	0.06	2.65	7.5	0.170	1.47E-08	N.A.	60(1)	
5.6	7.8	0.06	2.65	8.2	0.173	3.48E-08	1.42E-09	120(2)	
5.7	7.8	0.06	2.65	8.0	0.173	3.46E-08	N.A.	60(1)	
5.8	7.8	0.06	2.65	8.8	0.176	3.72E-08	N.A.	60(1)	
5.9	7.8	0.06	2.65	9.0	0.179	7.77E-08	4.76E-09	60(3)	
5.10	7.8	0.06	2.65	9.5	0.183	1.09E-07	8.62E-09	60(3)	
5.11	7.8	0.06	2.65	6.5	0.184	1.46E-07	2.32E-08	60(6)	
5.12	7.8	0.06	2.65	9.3	0.185	1.40E-07	1.07E-08	180(6)	
5.13	7.8	0.06	2.65	10.0	0.186	1.72E-07	1.10E-08	40(4)	
5.14	7.8	0.06	2.65	10.5	0.196	3.68E-07	2.32E-08	60(6)	
5.15	7.8	0.06	2.65	10.6	0.197	3.83E-07	1.20E-08	75(5)	
5.16	7.8	0.06	2.65	11.8	0.202	6.35E-07	2.13E-08	60(6)	
5.17	7.8	0.06	2.65	11.6	0.209	6.64E-07	6.22E-08	50(5)	
5.18	7.8	0.06	2.65	12.6	0.217	1.04E-06	4.46E-08	30(6)	
6.1	10	0.06	4.36	8.0	0.145	1.54E-08	2.63E-09	240(4)	>Figure 6a
6.2	10	0.06	4.36	9.4	0.158	7.07E-08	6.14E-09	180(6)	≈Figure 6b
6.3	10	0.06	4.36	10.5	0.167	1.52E-07	1.74E-08	120(6)	
6.4	10	0.06	4.36	11.2	0.178	4.64E-07	3.41E-08	60(6)	≈Figure 6c
6.5	10	0.06	4.36	13.6	0.192	9.00E-07	8.14E-08	60(6)	
6.6	10	0.06	4.36	15.6	0.207	2.22E-06	1.18E-07	30(6)	≈Figure 8b

vegetated flows should first be identified. Although quantitative methods (e.g., topography scanner and high-speed camera) were not used due to the limitation of the time and economic costs, a qualitative experiment was conducted to investigate the spatial variability of the sediment exchange under different flow conditions.

Observation shows that the sediment movements at different positions do not initiate at the same time when the flow rate is increasing. Hence, the bed sediment grains were marked before initiation to visually show the difference in their mobilities, which is similar to the method used by Einstein (1950) for revealing the mechanism of sediment exchange. To this end, the first layer of sand on the bed was dyed black before the commencement of the test. Once the black sands in a particular area on the bed were eroded, pale brown (original color) sands would be observed at the same place. Meanwhile, the other areas where the bed-load sediment was deposited or passed through would also be covered by brown sands. The areas that remained black were the bed regions without sediment exchanges.

The same experimental setup and procedure applied in measuring bed-load transport rates were repeated for the qualitative experiments. The two vegetation models with the lowest ($d = 7.8$ mm and $\phi = 0.66\%$) and highest densities ($d = 10$ mm and $\phi = 4.36\%$) were used as illustrations for discussion. In order to dye the sand on the bed surface, the sand bed was first carefully flattened. After that, Acrylic-Epoxy-based aerosol matt-black paint was sprayed on a 1-m-length full-wide bed area in the vegetation section at the downstream end. An appropriate amount of paint was sprayed to dye only the upper surfaces of the pale brown

Figure 3. A close aerial view of the undisturbed painted bed submerged in water.

sands on the most superficial layer (Figure 3). Besides, we also painted two 1-m-length, 30-mm-width longitudinal banded areas in the upstream vegetation section, with the intention to show the lateral dispersion of sediment transport (Figure 4a), if any. After the paint was dried, flows with different velocities were applied to scour the bed in the vegetation section. After the sediment transport has reached equilibrium, the flow was stopped and top-view images of the bed were captured after removing the vegetation models.

3. Results and Analysis

3.1. Phenomena

Although the spatial variability of the bed-load fluxes in vegetated flows had been highlighted by Yager and Schmeeckle (2013), its effect was excluded from the evaluation of bed-load transport rate in most of the previous studies (Yager & Schmeeckle, 2013; Yang & Nepf, 2018). In this section, several phenomena related to the spatial variabilities of sediment transport and bed forms are first presented before proposing a model to generalize the spatial distribution of the bed-load fluxes for different vegetation densities.

3.1.1. Spatial Variability of Sediment Exchange

First, the spatial distribution of the sediment exchange was investigated through the quantitative experiments described in Section 2.4. The present experimental observation reveals that the patterns of the bed-load transport under different flows can be categorized based on whether there is patch-scale sediment transport or global sediment exchange on the whole bed. Therefore, different flow velocities were applied to attain sediment transport with the categorized patterns. After the bed has reached the equilibrium scour state, top-view images of the painted region at the downstream end were captured. To illustrate the maximum lateral dispersion of sediment transport, an image of the banded painted regions was also captured (as Figure 4) after the corresponding test section had undergone scouring, subjected to the most intense flow through the densest vegetation. Additionally, specific cases were denoted in Tables 1 and 2, whose flow conditions are most comparable to those applied in the qualitative experiments.

Figure 4. Top-view image of the bed with two banded painted regions before and after being scoured by the same flow applied in Figure 6c: (a) the bed before adding flow; (b) top-view photograph of the scoured bed; (c) schematic diagram of the regions where the black sands were transported.

Figures 5 and 6 show top views of the bed which were captured in the experiment. The left and right halves of the figures, respectively, are the bed images and schematics that demarcate the bed zones where sediment exchanges had occurred. The bed particles in the dark areas are those without movement while the pale gray areas are areas with sediment exchanges. The white circles denote the vegetation stems. Based on the observed active areas of sediment exchange, the bed-load transport of different intensities is classified into three regimes: (1) Regime 1, local sediment motion; (2) Regime 2, incomplete global sediment transport; and (3) Regime 3, complete global sediment transport. The three bed-load transport regimes respectively represent different patterns of sediment motion.

As bed particles around the stems just started moving, the first regime of sediment mobility, namely “Regime 1: local sediment motion” was observed (see Figures 5a and 6a). In this regime, the bed particles saltate and roll in a small zone around the stem. No sediment particles are collected in the sediment trap, signifying that there is no net bed-load transport through the vegetation patch. Figure 5a clearly show that the gray-colored zones are not extended to the nearest downstream stem. It is deduced that the bed particles are merely moving locally, limited in

Figure 5. Top-view bed images for the case with the lowest vegetation density: $\phi = 0.66\%$, $d = 7.8$ mm. The different sediment-exchange regions show different regimes of the bed-load transport in vegetated flows: (a) Regime 1, local sediment motion, (b) Regime 2, incomplete sediment transport, and (c) Regime 3, complete global sediment transport.

the areas around the stems. In Regime 1, sediment motion around each stem is similar to clear-water scour around a bridge pier.

The second regime is reached with a higher flow intensity (as U_v shown in Figures 5b and 6b). The sediment-exchange regions develop and merge in the longitudinal direction, but are still separated in the transverse direction. The bed particles transport along a continuous sediment-exchange area through consecutively moving from the scour hole around one stem to another downstream. This is the “incomplete global sediment transport” regime, which is accompanied by particles transported into the sediment trap. Figure 5b and Figure 6b also show that some areas on the bed remain immobile, which are mainly the areas between the longitudinal rows of stems. Under this situation, the sediment motions around stems are akin to live-bed scour around rows of piers, with steady sediment input from upstream. Besides, in Regime 2, the lateral transport of bed-load fluxes is very slight, so no sediment moves across the immobile-bed region exist between two different longitudinal rows of stems.

In the third regime, called “Regime 3: complete global sediment transport,” sediment grains on every part of the bed are in motion which forms with the higher flow intensity. Figure 5c and Figure 6c show that

Figure 6. Top-view bed images for the case with the highest vegetation density: $\phi = 4.36\%$, $d = 10.0$ mm. The different sediment-exchange regions show different regimes of the bed-load transport in vegetated flows: (a) Regime 1, local sediment motion, (b) Regime 2, incomplete sediment transport, and (c) Regime 3, complete global sediment transport.

there are sediment exchanges on the entire bed, such that bed-load fluxes are also non-zero everywhere. In this case, a high-intensity bed-load transport rate can be readily measured and the lateral dispersion of sediments can be observed. Figures 4b and 4c are the bed images with banded painted regions being scoured by the same flow as that in Figure 6c. There is sediment transport from a stem to its nearest staggered stem downstream (see red arrows on Figures 5c and 6c). In this case, sediment motion in the entire vegetation patch resembles the live-bed scour of a group of piers. This regime is expected to be reached with a relative high discharge rate or high vegetation density.

According to the flow conditions of the qualitative experiments and the related cases that are denoted in Tables 1 and 2, it is deduced that all the bed-load measurements with $d = 7.8$ mm, $\phi = 0.66\%$ fall into Regime 2, but the measurements with $d = 10.0$ mm, $\phi = 4.36\%$ involve both Regimes 2 and 3. Hence, in the present bed-load-transport measurements with relatively high vegetation densities, the cases whose sediment transport rates are higher than a certain threshold fall into Regime 3. Although the thresholds between Regimes 2 and 3 cannot be accurately determined, they can be confined in certain ranges based on the measured velocities shown in Figures 5 and 6. For $d = 7.8$ mm, $\phi = 0.66\%$, the critical Re_d is between 2,477 and 3,071, and the critical k_s calculated using Equation 4 is in the range of $1.93 \times 10^{-3} - 2.92 \times 10^{-3}$,

while for $d = 10.0$ mm, $\phi = 4.36\%$, the critical Re_d is between 1,888 and 2,175, and the critical k_v is in the range of $2.91 \times 10^{-3} - 3.84 \times 10^{-3}$. Comparatively, the turbulence intensity (measured by k_v) is a better criterion to demarcate the threshold between Regime 2 and Regime 3 for different vegetation densities, but the threshold is not unified for different vegetation density. A rational reason is that the spatial variabilities of TKE in vegetation are different for different vegetation densities. Since k_v is a spatially averaged value, its critical value is smaller for a sparser vegetation distribution (e.g., $d = 7.8$ mm, $\phi = 0.66\%$). The precise threshold between Regime 2 and Regime 3 of the sediment-transport patterns needs to be studied by further experiments.

Besides, the bed-load measurements for the low and high densities both started when the transport rates were barely measurable, which should represent the lower boundary of Regime 2. However, the case with the highest density with an enhanced sediment transport rate reached Regime 3 much faster than the sparse case. It is reasonable to hypothesize that the range of Regime 2 on the transport rates will narrow down if the vegetation density becomes higher. Moreover, if we consider Regime 2 as a transitional regime, it is expected to disappear or be hardly distinguishable from Regime 3 for vegetations with a very dense distribution.

Notwithstanding various sediment transport patterns described above, the present study aims at proposing a bed-load transport model based on certain features of sediment transport in Regime 2, in order to evaluate all the sediment transports in Regime 2 (namely weak transport) and some moderately weak transports in Regime 3 (namely moderate transport). It is hypothesized that if the lateral dispersion in Regime 3 is low compared to the sediment transport along the longitudinal row of stems, the evaluation of the patch-scale transport rate can also be approximated using the mechanism of Regime 2.

According to the scoured bed with two 30-mm-width painted areas shown in Figure 4, the extent of lateral sediment transport was still very limited for the same case like that in Figure 6, whose bed-load transport was more intense than any of those in the present measurements. Therefore, all the cases of the present experiment in Regime 3 can be regarded as moderate sediment transport. The present bed-load measurements are representative of the weak and moderate bed-load transport through sparse-distributed vegetation (Nepf, 2012b).

3.1.2. Spatial Variability of the Bed-Load Fluxes

The foregoing descriptions reveal how the sediment exchange is heterogeneous on the bed surface. Arising from this, the various bed-load fluxes at different locations on the bed, that is $\overline{q_b}(x, y)$, are investigated, including their intensities and directions. Yager and Schmeeckle (2013) captured the particle trajectories to investigate the spatial distribution of the bed-load fluxes. Although they only obtained the longitudinal component of the bed-load fluxes, the corresponding two-dimensional bed-load fluxes can be derived according to an equilibrium hypothesis, that is,

$$\frac{\partial q_{bx}}{\partial x} + \frac{\partial q_{by}}{\partial y} = 0 \quad (5)$$

in which q_{bx} and q_{by} are the longitudinal and transverse components of the bed-load fluxes $\overline{q_b}(x, y) = (q_{bx}, q_{by})$, which is a vector field of the bed-load fluxes on the bed surface and (x, y) is the position on the bed as in Figure 7.

Yager and Schmeeckle (2013) presented the distribution of the longitudinal component of $\overline{q_b}$ (Figure 9a in their article, which is on the same area as that in Figure 7a). Thus, q_{by} in the same area can be calculated using Equation 5 based on the equilibrium hypothesis. Then, the intensity of $\overline{q_b}$ or the local bed-load transport rate at one point can be computed as

$$q_b = \sqrt{q_{bx}^2 + q_{by}^2} \quad (6)$$

Figure 7a shows the distribution of q_b , which is the scalar field of $\overline{q_b}$. It clearly reveals that the bed-load fluxes immediately downstream of and lateral to the stems are the most intense (marked in red in Figure 7a). The highest local bed-load transport rates are 10 times larger than those in the lateral areas (marked in blue in Figure 7a).

Figure 7. Spatial distribution of the bed-load fluxes was estimated based on the 2-D equilibrium, from the high-speed video measurements by Yager and Schmeeckle (2013): (a) contour map of the local sediment transport rate; (b) vector field of the bed-load fluxes. The bed-load experiment cited in the figure was conducted with $D = 0.5$ mm, $d = 13$ mm, $\phi = 1.70\%$, $U_V = 0.25$ m/s, which is most closely compared to Case 4.11 in Table 1.

Figure 7b is the vector field of $\overline{q_b} = (q_{bx}, q_{by})$. The calculation showed that $q_{bx} \gg q_{by}$, so the differences of the transverse components are hardly distinguishable in Figure 7b if the vector field is plotted sparsely. Thus, the arrows are plotted with a relative high density. Moreover, the arrowheads are omitted, because it is apparent that the primary directions of the bed-load fluxes follow the flow direction marked in Figure 7. Consequently, longer lines are used to scale $\overline{q_b}$, so that the transverse components will become more conspicuous in Figure 7b. With this approach, the areas where the lateral bed-load fluxes are more intense appear as a shadow in Figure 7b.

First, it is assumed that, for Regimes 2 and 3, the pattern of sediment motion in the present study is that all the bed particles are continuously moving from one scour hole to other downstream scour holes. It is of little possibility for a particle to be transported across a vegetation patch without being deposited into and entrained out of the scour holes. Based on this assumption, all the bed-load fluxes across a cross section can be traced to the scour holes. Once the local transport rates in the scour holes are evaluated, the patch-scale transport rate can be obtained by summation.

Second, there exists an appropriate cross section where the bed-load fluxes can be readily divided and respectively traced back to the upstream scour holes. Figure 7b shows that the transverse bed-load fluxes are nearly zero at the location immediately downstream of the stem (see the red dashed circled area) because the vectors of $\overline{q_b}$ essentially are parallel to the x direction. Moreover, there are also few transverse components in the adjacent lateral area (see the blue dashed circled area). Therefore, it is assumed that the transverse bed-load fluxes at the transverse cross section at about $x = 1.5$ cm downstream of a stem (see the green line in Figure 7b) where the transverse bed-load fluxes can be ignored. It is tenable to further assume that one can always find the cross section with little transverse bed-load fluxes in a vegetation patch with the similar staggered arrangement but different densities. According to Figure 7a, the bed-load fluxes through this cross section can be divided into two parts: (a) intense fluxes downstream of the stem (the red circled zone), and (b) weak fluxes in the area away from the stem (the blue circled zone). Thus, both parts of bed-load fluxes can be traced to the local scour holes where they are from and investigate the sediment motion in the corresponding scour holes.

In the following section, the bed forms generated by sediment transport are investigated to clarify the transport trajectories of the particles and how the patch averaged transport rate is determined by the local sediment motion around a stem.

3.1.3. Spatial Variability of the Scour and Deposition

Figure 8 shows images of the bed morphology captured during and after the bed was scoured, respectively, by the weakest and most intense sediment transport. The upper halves of the figure are top-view images and

Figure 8. Top and side views of the scoured bed: (a) two views of the scoured bed after measuring the lowest transport rate for the lowest density; (b) two views of the scoured bed after measuring the highest sediment transport rate for the highest density.

the lower halves are side-view images. The erosion and deposition induced by the vegetation stems generate scour holes adjacent to the stems and dunes downstream of the holes. The scour holes signify the regions with intensive sediment flux and the dunes signify the trajectories of the bed-load sediments after they are entrained from the scour holes. This is because bed forms are formed as the sediment is continuously transported through a specific area and this area can finally reach an equilibrium of deposition and erosion.

Figure 8a shows the image of the bed morphology (with stems being removed) obtained after measuring the lowest transport rate ($q_B = 2.26 \times 10^{-8} \text{ m}^2/\text{s}$) in the sparsest vegetation model ($d = 7.8 \text{ mm}$ and $\phi = 0.66\%$). It reveals that the dunes generated by sediment deposition downstream of the scour hole have a ridge shape. The ridges only connected two adjacent scour holes around the aligned stems but do not connect with other bed forms laterally, which indicates that the trajectory of sediment transport is also only in the longitudinal direction. Hence, the sediment transport obviously falls into Regime 2.

Figure 8b shows the bed forms after being scoured by the flow ($U_v = 0.207 \text{ m/s}$) through a vegetation patch with $d = 10 \text{ mm}$ and $\phi = 4.36\%$. The sediment transport must fall in Regime 3 because the bed forms are continuous on the whole bed, especially the staggered scour holes seem to be connected by the saddle-shaped bed forms. Hence, lateral sediment transport between the staggered scour holes likely are present. The trajectories of the bed-load fluxes at a position may not only have originated from the aligned scour hole.

Finally, by combining the above results, one can clearly distinguish the distinctive sediment transport patterns in Regime 2 and 3. It is apparent that the sediment-transport mechanism for Regime 2 is simpler. Sediment is only transported along the scour holes aligned in a row. The patch-scale transport is just the summation of all the sediment being transported along different rows of stems through a specific cross section. Moreover, because all the stems have a uniform size, the total transport rate can be solely determined by the sediment motion around an individual stem, which resembles a live-bed scour.

Nonetheless, it is inadvisable to propose a model that only works in Regime 2, otherwise, the model has little value for practical application. Actually, Regime 3 may be approximated by the model for Regime 2 when the errors are acceptable. This is because the sediment transport in Regime 3 is similarly dominated by the sediments entrained from the scour hole (Figure 7). If the main sources of the sediment transport are correctly evaluated, the bed-load transport rates in Regime 3 also can be predicted with little error.

Two main factors may produce errors for Regime 3. First, if the sediment transported from one scour hole to the staggered one is ignored, some sediment passing through a cross section as suggested in Figure 7 might be recounted. The prediction will, therefore, be overestimated. Second, because continuous bed forms are

Figure 9. Division of bed zones in which the bed-load fluxes are classified into different types. Vector field of the bed-load fluxes are defined by a segmented function.

generated on the whole bed, the development of the scour holes may be limited. Moreover, the bed-form induced turbulence will rise significantly. In this case, sediment motion cannot be evaluated by solely considering flows around an individual stem. The maximum dune height and scour depth in the present experiment are, respectively, 7 and 13 mm, which were measured with a point gauge (± 1 mm) after the most intense sediment transport (Regime 3, $q_B = 2.22 \times 10^{-6} \text{ m}^2/\text{s}$). The scour depth was much larger than the scour depth ($= 5.47 \text{ mm}$) generated by an isolated stem with the same approaching velocity (U_v), which is estimated through the method by Melville and Sutherland (1988). If only considering an individual stem scoured by the flow with turbulence induced by upstream stems, the influence of the bed-form turbulence on sediment transport may be another source of error.

Accordingly, the influence of the foregoing two factors on the transport rate should be minimized if the present measurements in Regime 3 are approximated by using the model for Regime 2. It, however, has been shown in Figure 7b that the staggered lateral bed-load transport is still insignificant in Regime 3 for moderate bed-load transport. Thus, for the present measurements in which the transport rates are lower than that in Figure 7, the lateral transport to staggered stems can also be ignored. Second, It can be deduced from Figure 8b, the development of the scour holes was not limited by the adjacent dunes because the scour depth was larger than those in the sparse vegetated flows (with the same bed-load transport rate). Thus, it is reasonable to assume that, even for the highest vegetation density in this study, the scour holes and flows in a vegetation

patch with multiple stems can be approximated by those around a single stem affected by the similar vegetation-induced turbulence.

3.2. Parametrization

3.2.1. Dimensionless Bed-Load Transport Rate

For a model that considers the bed-load fluxes only on part of the bed, it is not reasonable to use the commonly accepted dimensionless intensity of bed-load transport q_B^* proposed by Einstein (1950)

$$q_B^* = \frac{q_B}{\sqrt{\Delta g D^3}} \quad (7)$$

in which $\Delta = (\rho_s - \rho)/\rho$ is the submerged specific relative density of the sediment material with ρ_s and ρ being, respectively, the density of the sand and water; and g is the acceleration due to gravity.

In the present case, the parameter representing the patch-averaged bed-load transport rate only needs to describe the bed-load fluxes around the stems. Consequently, the zones with intense bed-load transport around the stems, and that connecting the two scour holes should be defined. The bed surface is therefore divided into two zones (Ω_1 and Ω_2) to generalize the distribution of bed-load fluxes (see Figure 9). A segmented function is used to describe the bed-load fluxes in each zone based on some rational simplifications as follows:

$$\overline{q_b}(x, y) = \begin{cases} (q_{bx}, q_{by}) & \text{in which } \int_{(x_0, y) \in \Omega_1} q_{bx} dy = q_B(L_y / 2l_y), \quad (x, y) \in \Omega_1 \\ (q_{bx}, q_{by}) & \text{in which } \int_{(x_0, y) \in \Omega_2} q_{bx} dy = q_B(L_y / 2l_y), \quad (x, y) \in \Omega_2 \\ (0, 0) & (x, y) \notin \Omega_1 \cup \Omega_2 \end{cases} \quad (8)$$

in which the bed-load fluxes in Ω_1 and Ω_2 are assumed to be non-zero; $x = x_0$ is assumed to be the cross section where the bed-load fluxes have only the longitudinal component. Ω_1 refers to the zones adjacent to

stems with intense bed-load fluxes; Ω_2 represents the zones connecting each Ω_1 , where the bed-load fluxes are weaker.

As mentioned in Section 3.1.2, it is assumed that the bed-load fluxes through the cross section $x = x_0$ in Figure 9 (denoted as the green line) have only the longitudinal component. Therefore, the sum of the local transport rates through the part of the cross section in one Ω_1 is the total transport rate in the scour hole around a stem. Besides, all the bed-load fluxes through the cross section in one Ω_2 are also the sediments transported from the upstream Ω_1 . Because the bed-load fluxes around each stems are supposed to be similar, the total transport rates through the cross section in Ω_1 and Ω_2 are the same. For a staggered vegetation distribution, it is surmised that the bed-load transport on the area around a stem with a width $L_y/2$ is concentrated on the cross section with the width l_y in a scour hole. Thus, the average transport rate through the cross section in Ω_1 is $q_B(L_y/2l_y)$.

Furthermore, we assume that the width l_y is affected by the stem diameter d and flow around the stem. Tang et al. (2013) reported that the width of the scour holes around the stems will increase if the flow intensity increases. Moreover it is deduced from the scale-effect study on pier-scour by Ettema et al. (1998) that l_y ($\approx$ the size of the scour hole) should be proportional to d for the same upstream flow condition. Thus, the width of Ω_1 can be expressed as

$$l_y / d = C_y f_y(U_v, \phi) \quad (9)$$

in which $f_y(U_v, \phi)$ is a function to evaluate influence of the approaching flow with additional turbulence, U_v is used to approximate the approach velocity, and ϕ is used to represent the vegetation-induced turbulence and C_y is a constant coefficient showing that all the other influential factors (including the flow depth h/d , sediment size D/d) that are fixed for the same case.

Consequently, the local average transport rate in Ω_1 is $q_b = q_B(L_y/2d)/f_y(U_v)$. The dimensionless bed-load transport rate in vegetated flows q_{Bv}^* , which describes the transport rate in Ω_1 , should be

$$q_{Bv}^* = \frac{q_B}{\sqrt{\Delta g D^3}} \cdot \frac{L_y}{2d} \quad (10)$$

It is noted that both $f_y(U_v, \phi)$ and C_y are omitted in Equation 10 because $f_y(U_v, \phi)$ can be embedded in the hydrodynamic parameter (dimensionless flow intensity) which will be derived in Sections 3.2.2 and 3.2.3, and C_y can be embedded in the predictive formula that will be determined by data fitting in Section 3.3.

Figure 10 presents the plot of $U_v - q_{Bv}^*$ with the data of the bed-load transport rates measured in this study. The data show that there are still significant differences between U_v for the same q_{Bv}^* but different vegetation densities ϕ . This clearly indicates the need for replacing U_v with a dimensionless hydrodynamic parameter that includes ϕ to collapse all the experimental data onto a unique curve. Moreover, if the stem sizes d are the same, the trends of data series in Figure 10 with different ϕ are nearly parallel. In contrast, for different d (7.8 vs. 10.0 mm), the trends of data series are not parallel. It is hence deduced that d is a factor that has influence on the relation between q_{Bv}^* and the flow conditions (e.g., U_v), so that d also needs to be included in the dimensionless hydrodynamic parameter. This parameter should account for the effect of flows around each vegetation stem on sediment transport and will be derived in the following sections.

It should be noted that, although using q_{Bv}^* instead of q_B^* to represent the bed-load transport rate is consistent with the hypothesis that most of the bed-load fluxes are transported across the scour holes, it cannot bring significant changes to the plot in Figure 10. This is because the additional term in q_{Bv}^* makes the data points in Figure 10 shift vertically, compared with those in a similar plot using q_B^* . The shifts of data points, that is, $L_y/2d$, however, only range from 3.0 to 7.7 in the present experiment. The differences in the shifts are marginal comparing with the tremendous increasing rate of q_{Bv}^* in Figure 10. Thus, adding $L_y/2d$ in q_{Bv}^* has little effect on reducing differences between the data series in Figure 10. Nonetheless, although the term $L_y/2d$

Figure 10. Bed-load transport rates measured with different vegetation densities and bulk flow velocities. The error bars indicate the standard deviation of the multiple measurements under the same flow condition.

still cannot be validated using the present data, it has a clear physical basis and is expected to be testified by future experiments using a wider range of L_y .

Besides, error bars for all the bed-load transport rates are also plotted in Figure 10 noted that all the errors for the transport rates measured in vegetated flows are not very significant. Some are even smaller than the size of markers in Figure 10. Furthermore, all the error bars are much smaller than the differences between q_{Bv}^* measured under different flow velocities U_v (the nearest gap between U_v is only about 0.01 m/s). It is opined that the measurement errors would not affect significantly the analysis of the influential factors on q_{Bv}^* in this study.

Furthermore, it is apparent from Figure 10 that the error bars for non-vegetated flows are larger than those for vegetated flows. A possible reason for this difference is that a vegetation patch may work as a “damping” section that keeps the flow and sediment transport in a flume more steady. It was observed in the present experiment that there was less volatility in the instantaneous discharge rate and no flume-scale waves or turbulence in vegetated flows. This may explain why the measurements of bed-load transport rates in vegetated flows have relatively low deviations.

3.2.2. Spatially Average Flow Intensity

In the study of bed-load transport on a sand bed without vegetation, the Shields number Θ is often used to describe the flow intensity:

$$\Theta = \frac{U_*^2}{\Delta g D} \quad (11)$$

in which U_* is the shear velocity that describes the boundary shear stress. However, U_* in vegetated flows is hard to be measured accurately. In flows with emergent vegetation, to some extent, the vertical profile of the mean velocity away from the bed surface is nearly uniform (Stoesser et al., 2010). If the total boundary shear stress is unchanged, U_v can be regarded as constant for any h that is large enough, hence U_v is supposed to have a constant linear relationship with U_* (Etminan et al., 2018). Accordingly, we use U_v to replace U_* in Equation 11 to define a parameter representing the spatially average flow condition in vegetated flows as

$$\Theta_v = \frac{U_v^2}{\Delta g D} \quad (12)$$

Figure 11. The experimental data of the bed-load transport in vegetated flows on the plot of $\Theta_v - q_{Bv}^*$: $D = 0.93$ mm, the present study; $D = 0.50$ mm, $d = 6.3$ mm, Yang and Nepf (2018); $D = 0.50$ mm, $d = 10.0$ mm, Armanini and Cavedon (2019); $D = 0.50$ mm, $d = 13.0$ mm, Yager and Schmeeckle (2013).

As shown in Figure 11, the experimental data measured in the present study and those by Armanini and Cavedon (2019); Yager and Schmeeckle (2013); Yang and Nepf (2018) are plotted on a double-log plot of $q_{Bv}^* - \Theta_v$. The figure shows that if the bed-load transport rate is evaluated by using Θ_v alone, the data for different vegetation densities are still scattered, rendering Θ_v alone inadequate and needs additional modification.

3.2.3. Flow Intensity Around a Vegetation Stem

The experimental data measured in the present study can be divided into two types according to the stem size ($d = 7.8$ mm and $d = 10.0$ mm). Figure 11 reveals that, if the stem size d is hold constant, the three curves representing the data with different ϕ are approximately parallel on the double-log coordinates. In other words, it can be surmised that the gradients of $q_{Bv}^* - \Theta_v$ curves with the same stem size d in Figure 11 are nearly the same, and differences between the curves are only horizontal offsets. This indicates that when generating the same intensity of bed-load transport q_{Bv}^* , there is a constant ratio between Θ_v for different ϕ .

The differences in Θ_v can also be shown in the data from other studies (Armanini & Cavedon, 2019; Yager & Schmeeckle, 2013; Yang & Nepf, 2018). It is, however, more difficult to ascertain if the differences in Θ_v are uniform for different q_{Bv}^* , because the previous measurements are quite scattered. Comparatively, the uniform differences in Θ_v is easily recognized from the present measured data because there are enough measurements that can precisely describe a $q_{Bv}^* - \Theta_v$ curve for each cases (see Figure 11).

This indicates that a multiplier (or coefficient) on Θ_v is needed for collapsing the data on the same curve. Although the differences in Θ_v are not sufficiently discussed in previous studies for bed-load transport, other studies for incipient motion investigated similar differences in the critical U_v . Yang et al. (2016), for example, found that $U_v + 6k_v^{1/2}$ is approximately a constant when the minimum bed-load transport rate can be measured for different vegetation distributions. Yang et al. (2016b) estimated the near-bed TKE in vegetated flows as $0.025U_v^2 + k_v$ and suggested that it is a criterion for the incipient motion. The ratio of the spatially averaged TKE k_v to the bulk flow kinetic energy $U_v^2 / 2$ in vegetated flows is defined as

$$K_v = \frac{2k_v}{U_v^2} \quad (13)$$

Thus, K_v can be evaluated from k_v through Equation 4 as

$$K_v = 2.4 \left(C_{Dv} \frac{\phi}{(1-\phi)\pi/2} \right)^{2/3} \quad (14)$$

where C_{Dv} is herein estimated through an approach by Cheng and Nguyen (2011):

$$C_{Dv} = \frac{50}{\text{Re}_v^{0.43}} + 0.7 \left[1 - \exp \left(-\frac{\text{Re}_v}{15000} \right) \right] \quad (15)$$

in which the vegetation Reynolds number Re_v is defined as

$$\text{Re}_v = \frac{U_v r_v}{\nu} \quad (16)$$

with a hydraulic radius for vegetation resistance r_v being proposed as

$$r_v = \frac{\pi}{4} \frac{1-\phi}{\phi} \quad (17)$$

It is found that K_v is approximately constant for the same ϕ , when U_v is in the range of flow conditions applied in the present study ($1,500 < \text{Re}_d < 3,500$).

In this case, the criteria for incipient motion proposed by the previous researchers can be regarded as U_v^2 multiplied by a coefficient factor, which contains K_v (i.e., $1 + 6\sqrt{2K_v} + 18K_v$, as proposed by Yang et al. (2016) and $1 + 20K_v$, by Yang et al. (2016b)). Accordingly, it is surmised that the coefficient on Θ_v for predicting the bed-load transport rate in vegetated flows also is likely related with K_v .

From the perspective of energy transfer, the spatially averaged kinetic energy of the vegetated flows is $U_v^2(1 + K_v)/2$. Hence, for the same U_v , if more intense turbulence is induced by vegetation, the bed-load transport rate will correspondingly be enhanced because more kinetic energy is transferred to the bed-load particles. However, it should be noticed that the influence of the intensified turbulence in enhancing the bed-load transport cannot be considered only based on its spatial average.

Based on the comparison of the experimental data for different cases, the differences in Θ_v for the same q_{Bv}^* in Figure 11 is much larger than the differences in $1 + K_v$. For example, when ϕ is increased from 0.0194 to 0.0436 (with $d = 10$ mm), $1 + K_v$ is risen from 1.13 to 1.25 (11% increase). However, the value of Θ_v for the same q_{Bv}^* has a nearly 40% reduction. Similarly, the large differences in Θ_v have also been confirmed by the experimental studies for defining the incipient motion condition (Yang et al., 2016, 2016b). In those cases, the constant coefficient of K_v is found to be much larger than 1.

Sumer et al. (2003) studied the bed-load transport on a sand bed (without vegetation) with externally induced turbulence. The intensity of bed-load transport is enhanced because the near-bed turbulence was increased by an array of grids fixed above the bed. It is found that, for the same extent of increase in spatial averaged turbulence, the enhancement of the bed-load transport rates in the present experiment are also much larger than that in the non-vegetated experiment by Sumer et al. (2003). Comparatively, turbulences are increased by some obstructions in the flows for the both experiments, however, the only difference is that the near-bed flow is spatially homogeneous in the experiment with a plane bed (Sumer et al., 2003), but highly heterogeneous in vegetated flows (the present study). It can be surmised that the large differences in U_v are due to the spatial variability in vegetated flows.

It can be elucidated from a quantitative analysis that the spatial variability can play a large influence on bed-load transport rate. In non-vegetated flows, bed-load transport rate q_B is quite sensitive to Θ . Lavelle and Mofjeld (1987) reported that the relation between bed-load transport and flow intensity can be formulated as $q_B^* \sim \Theta^n$, with n varying from 1.5 to 18 for different flow conditions. For moderate or weaker bed-load transport (i.e., $\Theta < 1$), n is at least larger than 5. Similarly, it is surmised that, in vegetated flows where the

Figure 12. Transfer of turbulent kinetic energy (TKE) with the shear flows around vegetation stem. Path is influenced by the stem; path is influenced by the stem, scour hole, and bed roughness; path is influenced by bed roughness.

spatial variability is significant, the sediments entrained from the bed areas with higher turbulence intensity (e.g., Ω_1) may also be largely increased following a power law. This has been supported by the observation in Figure 7a that the local transport rates in the intense-transport area (scour hole) are enhanced by an order of magnitude.

As illustrated in Figure 12, momentum exchanges between the flows obstructed by the stem and high-speed flows in the lateral areas generate intense shear flows. Because the shear flows around a stem is so complex, we regard the turbulent activities in the flows as a black box. Therefore, we just consider the kinetic energy in the shear flows, which is transferred from the approach flow. Figure 12 shows that the energy transfer can be originated from different upstream position, thus we approximate the approach flow to the stem by the patch-averaged vegetated flow (U_v, k_v).

From the perspective of the Reynolds average, the kinetic energy of the mean flow ($\approx U_v^2 / 2$) upstream a stem is largely transferred to the TKE in the scour hole because of the shear flows. Besides, the TKE in the upstream flow ($\approx k_v$) is also transported with the flow. Therefore, if turbulence dissipation is ignored compared to the enhanced TKE, it is assumed that the TKE of the near-bed flow in Ω_1 is totally contributed by the kinetic energy of the upstream approach flow away from the bed ($\approx U_v^2(1 + K_v) / 2$). It is assumed that the spatial variability amplifies the influence of turbulence on the sediment motion, so the extent of the amplification may be described based on $1 + K_v$. Specifically, the influence of the near-bed flow around a stem on the bed-load transport in Ω_1 is represented by the patch-average hydrodynamic parameter multiplied with a function of $1 + K_v$. Thus, we suggest that for the same stem and grain sizes, the flow intensity around the stem in Ω_1 is characterized by

$$\Theta_{v\Omega} = \Theta_v(1 + K_v)^n \quad (18)$$

where n is the exponent, in which $n > 1$.

It is assumed that for the same d and D , the spatial variability of flow around a stem does not change much with U_v . Therefore, the amplification on $1 + K_v$ induced by spatial variability is also nearly unchanged. Thus, n should be a constant for different ϕ . By fitting the present experimental data, it is calibrated that $n \approx 4$ for both $d = 7.8$ mm and $d = 10$ mm. Moreover, if n is also assigned as 4 for other experimental results cited in this study, those data are less scattered in the plot of $q_{Bv}^* - \Theta_{v\Omega}$ (Figure 13) than in Figure 11.

Figure 13. Comparison of the experimental data with different stem sizes d and grain sizes D on the plot of $\Theta_{v\Omega} - q_{Bv}^*$: $D = 0.93$ mm, the present study; $D = 0.50$ mm, $d = 6.3$ mm, Yang and Nepf (2018); $D = 0.50$ mm, $d = 10.0$ mm, Armanini and Cavedon (2019); $D = 0.50$ mm, $d = 13.0$ mm, Yager and Schmeckle (2013).

Figure 13 shows that, however, the experimental data collapse for the cases with the same d and D , but do not collapse across different cases with different sizes of stems or sediments. The curves that fit the data are approximated by the power-law relations, which are the straight trend lines depicted in Figure 13. Recognizing that the present experiment for the first time utilizes two types of vegetation stems in the same experimental setup, the curves for cases with $d = 7.8$ mm and $d = 10$ mm have different gradients. The two gradients are 9.41 for $d = 7.8$ mm and 7.16 for $d = 10$ mm. It is hard to visually distinguish the difference between the two gradients (the red and yellow dashed lines) in Figure 13 and evaluate the errors of the gradients caused by the scattering of data. However, the 95% confidence intervals for the gradients of linear-regressions, which are (8.61, 10.22) for $d = 7.8$ mm and (6.60, 7.72) for $d = 10$ mm, distinctly manifest that the two gradients are different. This indicates that the stem size may affect the trend of $q_{Bv}^* - \Theta_{v\Omega}$ data and should be included in the hydrodynamic parameter. Moreover, the curves for the data from the other studies with constant d but variant D also have different gradients in Figure 13. Thus, D should be considered in the parameter as well. It is also presented in Figure 12 that the shear flows which induce the turbulence in the scour hole may be affected differently by the length scales d and D according to different paths for transferring TKE. Therefore, the influences of d and D on the hydrodynamic parameter is so complex that that they can only be considered in a black box. The parameter representing the influences of d and D needs to be deduced based on the experimental data.

In order to adjust the gradients of the curves on the double-log coordinates, a power function is applied, including D/d as a parameter that affects the gradients in the plot. Hereby, the modified hydrodynamic parameter is proposed as

$$\Theta_{v\Omega}^* = (C_{\Omega} \Theta_{v\Omega})^{\exp(C_d D/d)} \quad (19)$$

in which C_{Ω} is the constant ahead of $\Theta_{v\Omega}$ and C_d is the constant in the exponent. The dimensionless stem size D/d is applied in the exponent because the gradients of the curves in Figure 13 increases with larger D/d . Considering the limiting condition of D/d , when D/d approaches 0, the limit of $\Theta_{v\Omega}^*$ is supposed to be a constant. This is because when the grain size is smaller than a certain level, it has little influence on the spatial variability in vegetated flows. Thus, it is assumed that the exponent of the power function of $\Theta_{v\Omega}$ is an exponential function, that is, $\exp(C_d D/d)$. Through fitting all the compile experimental data, C_{Ω} is calibrated as 0.22 and C_d as 15. In this case, all the data are presented on the plot of $q_{Bv}^* - \Theta_{v\Omega}^*$ as shown in Figure 14.

Figure 14. The experimental data of the bed-load transport in vegetated flows on the plot of $\Theta_{v\Omega}^*$ – q_{Bv}^* : $D = 0.93$ mm, present study; $D = 0.50$ mm, $d = 6.3$ mm, Yang and Nepf (2018); $D = 0.50$ mm, $d = 10.0$ mm, Armanini and Cavedon (2019); $D = 0.50$ mm, $d = 13.0$ mm, Yager and Schmeeckle (2013).

3.3. Prediction

Figure 14 shows that the data from the present study are collapsed on the same curve if q_{Bv}^* is plotted with $\Theta_{v\Omega}^*$. This indicates that $\Theta_{v\Omega}^*$ is a hydrodynamic parameter that can be used to generalize the flow intensity around the vegetation stem with different sizes. q_{Bv}^* is also an appropriate parameter representing the intensity of bed-load transport, which describes the bed-load transport in vegetated flows well.

The trend of the collapsed data is approximately a straight line on the double-log coordinates. Hence, a power function is used to fit the relation between q_{Bv}^* and $\Theta_{v\Omega}^*$ as follows:

$$q_{Bv}^* = \frac{(\Theta_{v\Omega}^*)^{1.63}}{240} \quad (20)$$

The curve of Equation 20, which is superimposed in in Figure 14 fits the present measurements very well ($R^2 = 0.956$). This excellent fit confirms that the power-law equation may be used to predict the transport rate of relative weak bed load transport ($q_{Bv}^* < 0.1$) in vegetated flows.

However, the experimental data from the other studies (Armanini & Cavedon, 2019; Yager & Schmeeckle, 2013; Yang & Nepf, 2018), which mostly have higher transport rates, are not in perfect agreement with the curve fitted by the data from the present experiment. Notwithstanding this deviation, the trends of the data from those studies have nearly the same gradient as the prediction curve. In other words, although the data from different studies are not collapsed, they have parallel trends. The discrepancy may be caused by the different relations between U_v and the upstream flow of a stem in different experiments, because the flow depths in all the studies are quite different. Moreover, relatively intense bed-load transport rates were also measured by some cited studies, which may have significant biases comparing with the present predictions obtained from the model that is based on weak bed-load transport.

Finally, Equation 20 is written as a general formula that can be used to predict the vegetation transport rates in vegetated flows with the parameter Θ_v :

$$q_{Bv}^* = \frac{(0.22\Theta_v(1 + K_v)^4)^{1.63\exp(15D/d)}}{240} \quad (21)$$

Figure 15. Determination of L_x in a randomly arranged vegetation patch.

in which K_v is calculated from Equation 14. The applicable conditions of Equation 21 are that the bed-load transport is weak or moderate and the vegetation distribution is sparse, that is $2d / (L_x^2 + L_y^2)^{1/2} < 0.56$ as suggested by Tanino and Nepf (2008b).

4. Discussion

The formula proposed for evaluating bed-load transport rates in the present study is based on a hypothesis of the pattern of sediment motion through emergent vegetation. However, the data obtained in the present study do not allow a complete validation of the hypothesis. This is because some factors that are related to physical mechanisms of sediment motion in the complex turbulence need to be investigated based on microscopic flow features and sediment motion. As a result, some of the parameters have to be determined empirically based on the experimental data.

Given the status of current studies for sediment transport in vegetated flows, the agreement between the model and data should never be the primary goal, because the experimental results are still insufficient and also subjected to large systematic errors. Alternatively, the present study aims to provide a tenable framework so that several assumptions can be verified and the bed-load formula can be improved to some extent. Two examples for the extendibility of this framework are presented as follows: (1) extending the present model to the vegetation whose arrangement is under practical conditions; (2) guiding the design of further experiments to verify the physical connections between the mechanisms of bed-load transport in vegetated flows and the proposed parameters q_{bv}^* and $\Theta_{v\Omega}^*$.

The present experiment was conducted with a staggered-arranged vegetation model, like most previous studies, which means that the stems have homogeneous and isotropic distributions. In real vegetation patches, however, the stems generally have a random arrangement and their distributions are usually anisotropic. Therefore, besides vegetation densities ϕ , the present model also uses L_x and L_y , which are not necessarily equal, to describe the geometric features of vegetation distribution. With this consideration, the proposed model is potentially applicable for field conditions as it accounts for the differences caused by different arrangements of vegetation.

For randomly arranged vegetation, L_x and L_y cannot be measured as being defined in Figure 2a. Alternatively, they may be calculated as explained in the following. First, L_x may be measured as the longitudinal distance in a circular sector (as shown in Figure 15), which has a specific acute central angle located at the upstream stem. Then, L_y is calculated as

$$L_y = \frac{\pi d^2}{2L_x \phi} \quad (22)$$

In which ϕ is obtained from the average count of stems per unit area. In this case, $L_y/2$ is the average transverse distance between two nearest regions with concentrated bed-load fluxes at a cross section (as in Figure 7). With the so-calculated L_y , the parameter q_{bv}^* still can be calculated from Equation 10 for random arrays of vegetation.

On the other hand, it should be noted that how to determine the central angle of the circular sector (in Figure 15) and the upper limit of L_x still requires further studies. The shape of the circular sector is supposed to be related to the lateral dispersion of sediment transport, which depends on flow intensities.

Furthermore, to explore the physical connection between the present model and the parameters, q_{bv}^* and $\Theta_{v\Omega}^*$, the parametrizations still need to be verified with additional experimental studies, for which the present study would be helpful for optimizing the design of experiments and the selection of parameters to be sampled.

Figure 16. Comparison between experimental data respectively measured by q^*_{Bv} and q^*_B .

First, it is noted that the influence of q^*_{Bv} on the agreement of data is not significant with the present data, but it can be further investigated with the experiment data of higher transport rates. Figure 16 shows that the relation between q^*_{Bv} and $\Theta_{v\Omega}$ is a monotonous increasing function. In contrast, among the data points in the plots using q^*_B , for $\Theta_{v\Omega} > 5$, some data points measured by the same studies do not show increasing trends. For example, as highlighted by the red circles in Figure 16, several points with nearly the same q^*_B respectively correspond to $\Theta_{v\Omega}$ whose values have very large differences.

Nevertheless, the difference between the influences of q^*_{Bv} and q^*_B is still not large enough, as shown in Figure 16, because the comparison is also affected by the measurement errors that have a similar scale as the differences induced by $L_y/2d$. Thus, to resolve the difference, it is suggested that future experiments could be done with an anisotropic vegetation arrangement ($L_y > L_x$) and a larger range of $L_y/2d$.

Second, the multiplication factor in $\Theta_{v\Omega}$ is also determined empirically. Because the factor $(1 + K_v)^n$ is used to represent an enhancement of the local bed-load transport rate associated with the live-bed scour, its validity can be confirmed by performing scour experiment around a cylinder affected by the upstream turbulence intensified by different sources.

Conducting such an experiment would be significant because studies of the influence of turbulence on live-bed pier scour are also lacking. At present, there is no motivation for researchers who study pier scour to conduct an experiment with such large D/d (corresponding to gravels or boulders) and under such live-bed conditions (for which the bed-load transport rate can be relatively large) that simulate the conditions of vegetated flows. However, according to the model proposed in this study, to apply the results of scouring experiments to vegetated flows, it is suggested that the scale of D/d should be based on the condition of real vegetation and the equilibrium bed-load transport rate needs to be measured during the intense live-bed scour. Moreover, because D/d is an influential factor added in $\Theta_{v\Omega}$, the scouring experiments should also cover a wide range of D/d . In this case, the flow features and sediment motions measured in the scour hole can well simulate the bed-load transport in vegetated flows.

In summary, the physical model proposed in this study sheds light on the design of experiments that need to be conducted in the future. Further studies could be conducted with anisotropic and random vegetation arrangements or focus on flow features in the scour holes around vegetation stems. It appears to be necessary to sample not only flow velocities at different positions among vegetation stems (Yager & Schmeckle, 2013; Yang & Nepf, 2018), but also those in the scour hole, which have the greatest influence on the spatial variability of the flow.

5. Conclusions

The present study aims at predicting the bed-load transport rates in flows with emergent vegetation. Experiments were conducted to observe the spatial variability of sediment motion around stems and measure the bed-load transport rates. Based on the data analysis as well as the physical observations, the following conclusions are deduced:

1. For the weak to moderate bed-load transport through a sparse vegetation patch, the sediment movement resembles live-bed scour around rows of piers aligned in tandem
2. The intensity of bed-load transport can be parametrized with the stem size d and the transverse distance between two adjacent stems in different rows $L_y/2$, representing the transport rate concentrated in the scour holes around the stems
3. Given the spatial distribution of the bed-load fluxes, a hydrodynamic parameter Θ_{Ω}^* is proposed by incorporating effects of ϕ and D/d to describe the local flow condition around a stem
4. The proposed model shows that the bed-load transport rate can be computed based on the local flow condition around the stems that governs the sediment transport between the scour holes. The spatial variability in the vegetated flow is considered in this model by only investigating the intense sediment motion in the scour holes, regardless the weak bed-load fluxes on other bed areas

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article. The experimental data from the present experiment have been presented in Tables 1 and 2. The compiled data from the previous experimental studies can be obtained from the publications by Armanini and Cavedon (2019); Yager and Schmeeckle (2013); and Yang and Nepf (2018). The data of the bed-load fluxes being used to generate Figure 7 is extracted from Figure 9 of the bed-load-fluxes distribution in the article by Yager and Schmeeckle (2013).

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