Influence of vegetation on spatial patterns of sediment deposition in deltaic islands during flood

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Abstract

River deltas are shaped by the interaction between flow and sediment transport. This morphodynamic interaction is potentially affected by freshwater marsh vegetation (e.g. *Sagittaria* spp. and *Typha* spp. in the Mississippi delta, USA) on the exposed surfaces of emergent deltaic islands. The vulnerability of deltaic islands is a result of external forces like large storms, sea level rise, and trapping of sediment in upstream reservoirs. These factors can strongly determine the evolution of the deltaic system by influencing the coupling between vegetation dynamics and morphology. In the last few years, models have been developed to describe the dynamics of salt marsh geomorphology coupled with vegetation growth while the effect of freshwater vegetation on deltaic islands and marshes remains unexplored. Here we use a numerical flow and sediment transport model to determine how vegetation affects the spatial distribution of sediment transport and deposition on deltaic surfaces during flood. Our modeling results show that, for an intermediate value of vegetation height and density, sedimentation rate increases at the head of the delta. On the other hand, large values of vegetation height and density promote more sedimentation at the delta shoreline. A logical extension of our results is that over time vegetation of intermediate height will create a steeper-sloped delta due to sediment trapping at the delta head, and taller vegetation will create a larger, but flatter delta due to

sediment deposition at the shoreline. This suggests intermediate vegetation height and density may create more resilient deltas with higher average elevations.

1. Introduction

Deltaic islands are individual marsh and sediment platforms surrounded on all sides by distributary channels. In many river deltas, these islands are the fundamental building blocks that create deltaic land (Fig. 1). Previous work (Fagherazzi et al., 2015 and references therein) have focused on their initial subaqueous formation due to sedimentation associated with turbulent jet expansion at the river mouth, whereas few studies have considered sedimentation processes on these islands once they are emergent and colonized with vegetation. This is surprising because sedimentation dynamics on vegetated island tops determines vertical accretion rates and delta resiliency to rising relative sea level. Understanding sedimentation dynamics on deltaic islands is critical since rising relative sea-levels are threatening to drown most of the world's deltas (Syvitski et al., 2009; Tessler et al., 2015). The purpose of this study is to investigate how the processes of mineral sedimentation on emergent deltaic islands are influenced by vegetation. This is especially relevant given the feedbacks between vegetation, mineral sediment transport, and morphodynamics shown to exist in fluvial systems (Murray and Paola, 2003; Tal and Paola, 2007) and salt marshes (Mudd et al., 2004; D'Alpaos et al., 2006; Kirwan and Murray, 2007; Temmerman et al., 2005; Temmerman et al., 2007; Fagherazzi et al., 2012).

Predicting deltaic island formation is complex because of the interactions of waves, tides, buoyancy effects, and longshore currents (Wright, 1977; Fagherazzi et al., 2015). We know from detailed numerical experiments how turbulent jet dynamics create sedimentation patterns leading to river mouth bar and eventually deltaic island formation (Edmonds and Slingerland, 2007; Rowland et al., 2010; Falcini and Jerolmack, 2010; Canestrelli et al., 2014), how those patterns are influenced by waves and tides (Nardin and Fagherazzi, 2012; Nardin et al., 2013; Leonardi et al., 2013), and how

those patterns change as a function of sediment characteristics and properties (Edmonds and Slingerland, 2010; Geleynse et al., 2011; Caldwell and Edmonds, 2014). Noticeably missing from these studies is an exploration on how emergent vegetation influences sedimentation on deltaic islands. Vegetation probably has little effect on the initial formation of subaqueous deposits at the river mouth because water is too deep for plant growth (see review in Fagherazzi et al., 2015). Once the island emerges and becomes nearly subaerial, it is typically shaped like a chevron pointing upstream, with sandy levees on the margins and a relatively smooth lower-lying interior (Fig. 1). The relief between the levee and island interior is usually small, but can vary depending on island age. In Wax Lake delta, Louisiana, USA, it is around 50 cm (Shaw et al., 2013; O'Connor and Moffett, 2015; Moffet et al., 2015). Vegetation that colonizes these islands is affected by small elevation differences. These elevation differences can change the hydroperiod, which is a key variable in determining species distribution (Hupp and Osterkamp, 1996; Wassen et al., 2002; Carle et al., 2014). For instance, the high sandy levees are usually colonized by trees, most commonly *Salix nigra* (black willow) in the Mississippi delta (Carle et al., 2014). The lower-lying interior is colonized by grasses such as *Typha* spp. (cattail), *Phragmites australis*, and floating submerged aquatic vegetation, such as *Nelumbo lutea* (American Lotus) (Carle et al., 2014).

Vegetation can grow and spread quickly across island surfaces (Johnson et al., 1985) and surprisingly few studies have examined how vegetation presence influences sedimentation dynamics of mineral sediment. The presence of vegetation on island surfaces could promote rapid vertical growth at the expense of basinward progradation if vegetation effectively traps sediment. But on the other hand, vegetated islands impose more friction on flood waters, which focuses water and sediment into the neighboring channels and increases erosion in non-vegetated areas (Temmerman et al., 2007; Nardin and Edmonds, 2014).

Figure 1. A) 2013 aerial photo of Wax Lake Delta, LA, USA (courtesy of Terra Metrics, Google Earth). Black solid line shows an example of island in Wax Lake Delta. B) Example image of normalized difference vegetation index (NDVI) data for Wax lake delta, LA, USA. Image is Landsat 7 ETM+ from Dec. 20th 2012.

A recent study by Nardin and Edmonds (2014) shows that an intermediate vegetation height maximizes deposition of non-cohesive sediment within the deltaic islands, while tall and dense vegetation deflects the flow and sediment in the distributary channels thus reducing island accretion. Nardin and Edmonds (2014) focused on the entire deltaic system, whereas our goal here is to determine the spatial distribution of sediment fluxes on individual deltaic islands and their relationship to vegetation characteristics during flood events. Here we report on numerical experiments using Delft3D. Our vegetation experiments are non-morphodynamic since we are primarily interested in how vegetation impacts the spatial distribution of sedimentation during floods. This paper is organized as follow: in Section 1, we briefly describe the numerical model Delft3D utilized to simulate sediment fluxes and the equation from Baptist (2005) used for modeling vegetation effects on deltaic islands (from now on referred as Baptist's equation). In Section 2 we report the model set-up and the simulation parameters utilized in our model runs. Section 3 presents a set of hydrodynamic and morphodynamic

90 implications stemming by the presence of vegetation. We then analyze the spatial distribution of
 91 sediments on deltaic surfaces and the morphodynamic implications for delta evolution and resiliency.
 92 Section 4 presents a discussion of the numerical results and a connection to the previous published
 93 studies, while a set of conclusions is outlined in Section 5.

94 **2. Modeling sediment fluxes on the vegetated islands**

95 The hydrodynamic and morphodynamic model Delft3D was chosen for our analysis (Deltares, 2013).
 96 All of our simulations are depth-averaged because the vertical structure of the vegetation is neglected
 97 and the vertical velocity on the deltaic islands is usually small. We thus use the 2D version of the
 98 model, reducing computational time and simplifying the investigated problem. Here we present the
 99 main characteristics of the model together with the model setup for our simulations. Further details on
 100 the model can be found in Deltares (2013) and Lesser et al. (2004).

101

102 **2.1 Model description**

103 The two-dimensional version of the model Delft3D solves the fluid flow, sediment transport, and
 104 morphological evolution in a coupled fashion. Defining a coordinate system (x, y, z) with the x -axis
 105 longitudinal, the y -axis transversal, and the z -axis vertical upward, the system of shallow water
 106 equations governing fluid flow reads:

$$107 \quad \frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} = -g \frac{\partial \eta}{\partial x} + g \frac{U(U^2 + V^2)^{1/2}}{c_b h} + \frac{\partial}{\partial x} \left(\nu_H \frac{\partial U}{\partial x} \right) + \frac{\partial}{\partial y} \left(\nu_H \frac{\partial U}{\partial y} \right) \quad (1)$$

$$108 \quad \frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} = -g \frac{\partial \eta}{\partial y} + g \frac{V(U^2 + V^2)^{1/2}}{c_b h} + \frac{\partial}{\partial x} \left(\nu_H \frac{\partial V}{\partial x} \right) + \frac{\partial}{\partial y} \left(\nu_H \frac{\partial V}{\partial y} \right) \quad (2)$$

$$109 \quad \frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \quad (3)$$

110 where U and V are the velocities in x and y directions, η is the elevation of the water surface, h is the
111 water depth, C_b is the bed roughness according to Chezy, g is the gravity acceleration, ν_H is the
112 horizontal eddy viscosity.

113 The sediment-transport and morphology modules in Delft3D account for bedload and suspended-load
114 transport of cohesive and non-cohesive sediments and for the exchange of sediment between bed and
115 water column. Suspended load is evaluated using the sediment advection–diffusion equation, and bed-
116 load transport is computed using empirical transport formulae. Sediment-transport and morphology
117 modules in Delft3D allow transport of multiple sediment fractions. The transport of each sediment
118 class is separately calculated taking into account the availability of each fraction in the bed. Bedload
119 transport for non-cohesive sediment is computed with the formula of van Rijn (1993), while the
120 suspended-load transport is calculated by solving the diffusion-advection equation:

$$121 \quad \frac{\partial c}{\partial t} + U \frac{\partial c}{\partial x} + V \frac{\partial c}{\partial y} = \frac{\partial}{\partial x} \left(\varepsilon_s \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left(\varepsilon_s \frac{\partial c}{\partial y} \right) + \frac{c_{eq} - c}{T_s} \quad (4)$$

122 where c is the suspended sediment mass concentration, ε_s is the sediment eddy diffusivity, T_s is an
123 adaptation time scale, and c_{eq} is the local equilibrium depth-averaged suspended sediment
124 concentration. In case of cohesive sediments, the Partheniades–Krone formulations for erosion and
125 deposition are used (Partheniades, 1965). In these formulations, the critical shear stress for erosion is
126 always greater than or equal to the one for deposition; therefore, intermediate shear-stress conditions
127 may exist for which neither erosion nor deposition occurs (see Delft3D manual for full reference).

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129 **2.2 Effect of vegetation on flow**

130 The model Delft3D allows users to specify bed roughness and flow resistance on a sub-grid level by
131 defining various land use or roughness classes. One way to model vegetation in Delft3D is to correct
132 the bed roughness using the equation proposed by Baptist (2005). Baptist's formulation is based on the

133 concept that vegetation can be modeled as rigid cylinders characterized by height h_v , density m , stems
 134 diameter D , and drag coefficient C_D . In this formulation the velocity profile is divided in two flow
 135 zones: 1) a zone of constant flow velocity, u_v , inside the vegetated part and 2) a logarithmic velocity
 136 profile, u_u , above the vegetation starting from the velocity value u_v at the vegetation interface (Fig. 2).
 137

138
 139 Figure 2. Schematization of the velocity profile in the Delft3D vegetation model. A) Vegetation
 140 partially submerged and B) fully submerged. Modified from Nardin and Edmonds (2014).
 141

142 For the case of fully submerged vegetation (Fig. 2B), the total shear stress, τ_t is given as:

143
$$\tau_t = \rho g h i = \tau_b + \tau_v \quad (5)$$

144 where ρ is the water density, g is the gravity acceleration, i is the slope of the water surface, h is the
 145 water depth. τ_t is equal to the sum of the bed shear stress, τ_b , and the shear stress due to the vegetation
 146 drag, τ_v :

147
$$\tau_b = \frac{\rho g}{c_b^2} u_v^2 \quad (6)$$

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$$\tau_v = \frac{1}{2} \rho C_D n h_v u_v^2 \quad (7)$$

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where C_b is the bed roughness according to Chézy, C_D is the drag coefficient of the vegetation structure, $n = m D$ is the vegetation density, h_v is the drag coefficient of the vegetation structure, m is the number of stems per unit area, and D is the diameter of cylinders.

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Figure 3. A) Computational domain and boundary conditions. B, C and D) Domains of 3 pre-formed river deltas, respectively Delta1, Delta 2, and Delta 3. Colors show bed level in the domain while black lines define marsh surfaces. White letters on deltas identify the names of deltaic islands. The red box in D) shows the computational domain for channel shear stresses.

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By Replacing τ_b and τ_v in Eq. (5) with the expressions given in (6) and (7), it is possible to calculate the uniform velocity from the momentum balance equation as:

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$$u_v = \sqrt{\frac{hi}{C_b^{-2} + (2g)^{-1} C_D n h_v}} \quad (8)$$

Combining Eq. 6 and Eq. 8 yields an expression for the vegetated bed shear stress, τ_{bv} , as a function of a reduction factor, f_s , times the total shear stress τ_t for the uniform flow velocity through the vegetation:

$$\tau_{bv} = f_s \tau_t, \quad f_s = \frac{1}{1 + \frac{C_D n h_v C_b^2}{2g}} \quad (9a,b)$$

The Chézy friction value for totally submerged vegetation, C_{rs} , is defined as:

$$C_{rs} = \frac{\bar{u}}{\sqrt{h i}} \quad (10)$$

where $\bar{u}$ is the depth-averaged flow velocity. Introducing Eq. 5 and Eq. 10 in Eq. 9a, one can obtain the expression:

$$\tau_{bv} = f_s \frac{\rho g}{C_{rs}^2} \bar{u}^2 \quad (11)$$

where C_{rs} (see details in Baptist, 2005) is defined as (see details in Baptist, 2005) :

$$C_{rs} = \sqrt{\frac{1}{C_b^{-2} + (2g)^{-1} C_D n h_v}} + \frac{\sqrt{g}}{k} \ln \left(\frac{h}{h_v} \right) \quad (12)$$

where k is the Von Karman constant ($k = 0.4$). In the case of partially submerged vegetation, following the same procedure for fully submerged vegetation and adding bed shear stress, τ_b , and the shear stress due to the vegetation drag, τ_v , in Eq. 5, we obtain:

$$ghi = \left(\frac{1}{2} C_D n h + \frac{g}{C_b^2} \right) u_v^2 \quad (13)$$

The uniform flow velocity is:

$$u_v = \sqrt{\frac{h i}{C_b^{-2} + (2g)^{-1} C_D n h}} \quad (14)$$

178 in this case $u_v = \bar{u}$. Combining Eq. 6 and Eq. 14, the bed shear stress due to the flow velocity through
 179 the vegetation, $\tau_{bv,ns}$, becomes:

$$180 \quad \tau_{bv,ns} = f_{ns} \tau_t, \quad f_{ns} = \frac{1}{1 + \frac{C_D n h C_b^2}{2g}} \quad (15a,b)$$

181 The main difference between the two cases of submerged and emergent vegetation is in the reduction
 182 factor which in the first case includes the vegetation height, h_v (Eq. 9b), while in the second case
 183 contains the water depth, h (Eq. 15b).

184 The representative Chézy value for non-submerged vegetation is defined by:

$$185 \quad C_r = \frac{u_v}{\sqrt{h i}} \quad (16)$$

186 Introducing Eq. 8 in Eq. 16 the Chézy roughness coefficient for non-submerged vegetation becomes:

$$187 \quad C_r = \sqrt{\frac{1}{C_b^{-2} + (2g)^{-1} C_D n h_v}} \quad (17)$$

188 Therefore in Eq. 12 the first term on the right hand side equals the representative roughness for the
 189 partially submerged vegetation if $h = h_v$. Moreover, the value of C_{rs} is higher than the value of
 190 C_r leading to a smaller resistance for fully submerged vegetation. In our formulation we do not account
 191 for capture of sediment particles by vegetation (Mudd et al., 2010).

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193 **2.3 Setup of hydrodynamic model**

194 We simulate water flow and sediment transport on a computational grid of 500 by 750 cells, each
 195 10x10 m in size (Fig. 3). The basin has an initial slope of 0.0004 to the north, creating depths between
 196 1 and 3.5 m, comparable to those found in the Wax Lake delta, Louisiana (Wellner et al., 2005; Shaw
 197 et al., 2013). Initial depths are then adjusted adding random variations uniformly distributed between 0
 198 and 5 cm to simulate natural bottom variations. A rectangular river channel 250 m wide, 3 m deep and

199 extending 500 m toward the basin is carved into a sandy shoreline along the southern boundary of the
200 grid. Tests show that the shoreline width does not alter the numerical results. The lower, upper, and left
201 boundaries are open with a constant water surface elevation equal to zero (Fig. 3A). Five meters of
202 mixed non-cohesive and cohesive sediments are initially available for erosion at the bottom of the
203 domain.

204 We utilize the Van Rijn (1993) transport formulation for non-cohesive sediments, and the erosion
205 and deposition shear stresses are based on the Shields parameter for sediment re-suspension. For
206 cohesive sediments we use the Partheniades-Krone formulation. The boundary conditions consist of
207 equilibrium flow for the non-cohesive fraction and a set concentration of cohesive sediment (0.5
208 kgm^{-3}). The suspended sediment eddy diffusivities are a function of the fluid eddy diffusivities and are
209 calculated using horizontal large-eddy simulations and grain settling velocity. The horizontal eddy-
210 viscosity coefficient is defined as the combination of the subgrid-scale horizontal eddy viscosity,
211 computed from a horizontal large-eddy simulation, and the background horizontal viscosity here set
212 equal to $0.001 \text{ m}^2 \text{ s}^{-1}$. Bed roughness is set to a spatially and temporally constant Chézy value of 45
213 $\text{m}^{1/2} \text{ s}^{-1}$. A time step of 6 s is adopted to satisfy all stability criteria.

214 The first step in our modeling experiments is to create each delta shown in Fig. 3. Starting from an
215 empty basin, we allow the delta to evolve under a steady discharge of $1,250 \text{ m}^3/\text{s}$, carrying an
216 equilibrium concentration for both non-cohesive sediments ($D_{50} = 100 \text{ }\mu\text{m}$, $\rho = 2,650 \text{ kg/m}^3$) and
217 cohesive sediment ($D_{50} = 25 \text{ }\mu\text{m}$) until the morphology reaches dynamic steady state. We define this
218 state as the point when the slope of the delta surface does not significantly vary in time. The second
219 step in our modeling experiments is to add vegetation to the delta. After dynamic steady state is
220 achieved, we selected three different deltaic configurations (Fig. 3) and populated all the parts of
221 deltaic islands above sea-level (defined as zero elevation) with a uniform vegetation of a given height

222 and density. For our vegetation experiments we ran 101 simulations by varying vegetation height, h_v ,
223 from 0.05 m to 1.5 m and different density, n , from 0.05 m⁻¹ to 0.5 m⁻¹ (Table 1).

224 The ranges of vegetation density and stem diameter used herein are supposed to encapsulate values
225 typical of *Typha latifolia*, a common species in the Wax lake delta, Louisiana (Johnson et al. 1985).
226 *Typha latifolia* has a density of ~40 stems per square meter (Grace 1989; Miller and Fujii, 2010) and a
227 stem diameter of ~1 cm (Kadlec and Wallace, 2009). These vegetation parameters result in $n= 0.4$,
228 which is within the range of values used in our simulations. In terms of vegetation height, our non-
229 dimensional values are consistent with the fact that on the Wax Lake Delta immature vegetation is
230 often submerged, while more mature vegetation would likely remain emergent for a range of floods
231 (Johnson et al., 1985).

232 We then subjected one delta (Delta 1) to different floods, Q_b , from 2,500 to 5,000 m³s⁻¹ to evaluate
233 how vegetation affects sediment transport and deposition on delta islands during different flood events.
234 We use the other two deltas, called Delta2 and Delta3, to test how different configurations affect
235 sediment distribution. Our vegetation experiments are non-morphodynamic and are only designed to
236 assess how vegetation impacts the spatial distribution of sedimentation and erosion during floods.

237 All of our simulations are depth-averaged because the vertical structure of the vegetation is
238 neglected and the vertical velocity on the deltaic islands is usually small. We thus use the 2D version of
239 the model, reducing computational time and simplifying the investigated problem. On each deltaic
240 island we compute the total water volume, the average sediment concentration, and the input and
241 output sediment fluxes. This approach offers the possibilities to analyze large-scale flow and transport
242 patterns and to easily plot time series of fluxes for each island.

243 To compare different runs, we define a non-dimensional vegetation height as $\widehat{h}_v = \frac{h_v}{\bar{D}}$, where $\bar{D}$ is
244 the mean water depth on the islands for a given run. To decouple the action of vegetation on water and
245 sediment fluxes, we compute a control run without vegetation for each water discharge, Q_i , and delta

246 configuration. The model setup adopted herein represents a fluvial dominated delta in which waves,
247 tides and other coastal processes are negligible. These conditions are very common in deltas that are
248 characterized by higher water and sediment discharge like in rivers debouching in a lake or in a low
249 energy coast (e.g. Wax Lake delta in Louisiana). Moreover, during a flood event, river discharge is
250 dominant compared to marine processes. If tides and waves interact with the flow at the edge of the
251 delta, the vegetation influence on water depth becomes more complex (e.g. Leonardi et al., 2013;
252 Nardin et al., 2013; Fagherazzi et al., 2015).

253 **2.4 Shoreline definition method**

254 To define the shoreline, we apply the Opening Angle Method (OAM) proposed by Shaw et al.
255 (2008). The OAM is an image-based method for shoreline mapping that uses a visibility criterion. The
256 OAM method defines the coast-sea boundary where the shoreline is ambiguous, for instance across
257 channel mouths. Once the shoreline is defined, we start the analysis of the fluid and sediment fluxes
258 across it. We also divide the delta area in different slices using OAM. Each slice is defined by the
259 fractional distance from the river mouth (the shoreline is 100% of the delta extension while the river
260 mouth is 0%).

261

262 **3. Modeling Results**

263 **3.1 Effect of vegetation on water fluxes**

264 To understand how vegetation affects water fluxes in the delta during floods, we analyze the total water
265 flux over and through the islands (F_b) in the presence of vegetation (Fig. 3). We find that, for a given
266 incoming river discharge Q_i , increasing $\widehat{h}_v$ and n increases the amount of water in the channels and
267 reduces the fraction of discharge flowing on the islands, $R_w = \frac{F_b}{Q_i}$, by up to 20% (Fig. 4). This reduction
268 occurs because the main effect of vegetation is to increase the roughness of the islands causing water to

269 seek the smoother, less resistant paths through the channels. This process, already showed in Nardin
 270 and Edmonds (2014) has also been observed for tidal channels in salt marshes (D'Alpaos et al., 2006;
 271 Temmerman et al., 2007). The amount of water flux on the islands, R_w , decreases with denser
 272 vegetation (Fig. 4). In all cases, there is minimal change in R_w when $\widehat{h}_v > 1$ because the vegetation is no
 273 longer submerged and increasing vegetation height has minimal effect on resistance. For fixed water
 274 discharge Q_i (i.e. for a given line color in Fig. 4) and vegetation height, h_v , the reduction of R_w is
 275 controlled by the vegetation density n , which over the parameter space explored here deflects 10% -
 276 25% of water from the islands to the channels.

277
 278 Figure 4. Steady state water fluxes on all marsh surfaces normalized with respect to the river discharge
 279 ($R_w = F_b/Q_i$) as a function of non-dimensional vegetation height ($\widehat{h}_v$).
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281 We find a complex relationship between R_w and Q_i . Increasing the river discharge from $2Q_i$ to $3Q_i$
 282 causes an increase in R_w for a given n . On the contrary, an increase to $4Q_i$ causes R_w to decrease,
 283 suggesting that an intermediate river discharge maximizes water flux onto the islands (Fig. 4). Our
 284 model results seem to be not affected by the delta shape as we find identical trends for different deltas
 285 (Fig. 4).

286

287 Figure 5. Water fluxes on selected deltaic islands (see Fig. 3) normalized with respect to the case
 288 without vegetation ($F_w = F_b / F_{bnv}$) as a function of non-dimensional vegetation height ($\hat{h}_v$). A) Delta1,
 289 B) Delta2, and C) Delta3.

290

291 We also explore how the normalized water flux on each island, $F_w = F_b / F_{bnv}$ where F_{bnv} is the flux in
 292 the absence of vegetation, varies for different islands within the delta (Fig. 5). In agreement with the
 293 analysis on the entire delta, F_w on each island generally decreases for higher vegetation height.

294 However, some islands display a different behavior depending on their position relative to the delta
 295 head. In fact, distal islands display a decrease in F_w until $\hat{h}_v = 0.5$ followed by an increase for taller
 296 vegetation (see, for example, Island 2 in Fig. 5).

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299 Figure 6. A) Spatial distribution of normalized depth-averaged velocity R_U and B) normalized water
 300 depth R_D for each computational cell for a vegetation height of 0.5m and density of 0.5 on Delta3.
 301 Black lines show the polygon boundaries where water fluxes are calculated. C) Delta-wide average of
 302 R_U nonlinearly decreases as a function of non-dimensional vegetation height $\hat{h}_v$. D) Delta-wide average
 303 of R_D nonlinearly increases as a function of $\hat{h}_v$. E) R_U averaged for individual islands and F) R_D
 304 averaged for individual islands on Delta3 as a function of $\hat{h}_v$ non-dimensional vegetation height.
 305 Dashed black circles on C) and D) show the run displayed in A) and B).

306 We define other two non-dimensional ratios for water depth $R_D = \frac{\bar{D}_v}{\bar{D}_{nv}}$ and velocity $R_U = \frac{\bar{U}_v}{\bar{U}_{nv}}$ to
 307 determine the influence of vegetation on water fluxes. We calculate the spatially averaged water depth
 308 $\bar{D}$ and velocity $\bar{U}$ on all the computational cells inside each island in the presence of vegetation (v) and
 309 without (nv) (Fig. 6C-F), whereas we take the local ratio (no averaging) for a given computational cell
 310 in Fig. 6A and B. We find that the additional roughness caused by the vegetation increases the water
 311 depth R_D (Fig. 6B and D), possibly diverting more water on the islands and thus increasing R_w (Fig.
 312 4). However, the velocity R_U decreases as well (Fig. 6A and C), offsetting the increase in R_D (Fig. 6C
 313 and 6D), and leading to a total reduction in R_w and an increase in channel water flux.
 314 Figure 6B shows that water depth increases in the central part of the islands due to vegetation. Note
 315 that water level on the islands is reduced at the shoreline because of the influence of sea level. For
 316 fixed $\widehat{h}_v$ and n , our model results show a rising mean water depth with higher river discharge. On the
 317 contrary, the normalized velocity on deltaic islands does not substantially change for different river
 318 discharges.
 319 Local hydrodynamics on specific islands in Delta3 (Fig. 6E and 6F) roughly agrees with the general
 320 trend observed for depth averaged velocity and water depth. In Fig. 6E, R_U as a function of $\widehat{h}_v$ is
 321 similar for different islands within Delta 3. On the other hand, R_D shows two slightly different
 322 behaviors depending on the distance from the delta apex. In fact, islands at the head of the delta such
 323 as D_3^1 , D_3^4 and D_3^5 shows a sharp increase in R_D with larger $\widehat{h}_v$ (Fig. 6F). On the contrary, distal islands,
 324 such as island D_3^2 and D_3^3 , are characterized by smaller R_D (Fig. 6) because of the influence of the
 325 nearby sea level, which prevents the formation of steep gradients in water surface.

326 **3.2 Effect of vegetation on shear stresses**

327 While vegetation changes the magnitude and direction of water fluxes on the delta, it also changes
 328 patterns of erosion and sedimentation within the islands and in the distributaries. Defining the mean

329 shear stress ratio on the islands as $\hat{\tau}_{bar} = \frac{|\bar{\tau}_{island}|_v}{|\bar{\tau}_{island}|_{nv}}$ and in the channels as $\hat{\tau}_{ch} = \frac{|\bar{\tau}_{ch}|_v}{|\bar{\tau}_{ch}|_{nv}}$, allows us to

330 assess how vegetation affects shear stress on deltaic landforms. Fig. 7A shows that the mean bottom

331 shear stress on the different islands in the presence of vegetation decrease up to 90% compared to the

332 non-vegetated case. For $\widehat{h}_v > 1$ we detect a minimal change in $\hat{\tau}_{bar}$ because when the vegetation is not

333 submerged an increase in vegetation height has minimal effect on bottom shear stresses. Moreover, the

334 presence of vegetation on deltaic islands increases the water fluxes in the channels surrounding the

335 islands, increasing water velocity (Fig. 6B and D) and consequently the bottom shear stress by up to

336 50% compared to the case without vegetation (Fig. 7B, the mean value of $\hat{\tau}_{ch}$ is computed in the

337 channel reach shown in Fig. 3D). Finally, an increase in velocity leads to more sediment transport

338 within the channels as shown in Fig. 8.

340 Figure 7. Average bed shear stress A) on all marsh surfaces and B) in the main river channel portion
 341 (see red box in Fig. 3D) as a function of non-dimensional vegetation height ($\widehat{h}_v$).
 342
 343

344 3.3 Effect of vegetation on sediment fluxes, and patterns of erosion and deposition

345 Our results show that for low values of $\widehat{h}_v$ and n there is more sediment delivered to the marshes at the

346 head of the delta (Fig. 8B) and less sediment available for the distal parts of the delta (Fig. 8C and D).

347 On the contrary, for high values of $\widehat{h}_v$, the sediment transport is confined in the channels at the head of
 348 the delta and delivered to the delta shoreline as shown in Fig. 8C and D.

349

350

351 Figure8. A) Locations of three cross sections S1, S2, S3 on Delta3 where sediment transport values
 352 were measured. B), C) and D) total non-cohesive sediment transport through S1, S2 and S3. The total
 353 transport decreases on inner deltaic islands for high non-dimensional vegetation height ($\widehat{h}_v=0.92$),
 354 while it increases in the channel thus delivering more sediment to the delta edge. The sections farther
 355 from the delta head (C and D) show a high sediment transport on the distal islands when high
 356 vegetation is present.

357

358 To better understand the effect of vegetation on the spatial distribution of sediment deposition, we
 359 select two different areas of the delta, one at the delta head and one at the delta shoreline, and compare
 360 sediment deposition for different vegetation heights (Fig. 9A and B). These runs are not
 361 morphodynamic because changes in bed elevation are not used to update water velocity. For the distal
 362 islands, our results show more sediment deposition for $\widehat{h}_v=2.81$ while erosion is present for $\widehat{h}_v=0.15$
 363 (Fig. 9D). This higher deposition is triggered by high sediment transport in the channels near the delta
 364 head; the sediment thus bypasses the inner islands and it is delivered to the outer islands (Fig. 8).

365 Fig. 9A and B highlight differences in the erosion and deposition patterns on Delta 1, with $\widehat{h}_v$ non-
 366 dimensional of 0.15 and 2.81. Low riparian vegetation height leaves the surface exposed to high shear
 367 stresses during flood. Levees form far away from the original river channel (Fig. 9C). As vegetation
 368 height increases, the hydraulic roughness of the marsh increases and more water is deflected into the

369 channels. There is still sedimentation at the distributary margins, which creates levees, but as
 370 vegetation height increases the levees become narrow, smaller, and positioned closer to the river bank
 371 (Fig. 9C). On distal islands the opposite behavior is observed: for high vegetation values, more
 372 sediment is deposited on the island building large levees and reducing erosion. The development of
 373 sandy levees could create an eco-geomorphological feedback that blocks the water and associated
 374 sediment flux coming from the channels, funneling more water and sediment downstream.
 375

377 Figure 9. A) and B) Erosion and deposition patterns on deltaic islands, for $n=0.5$, $Q_i=2.500 \text{ m}^3\text{s}^{-1}$:
 378 A) $\widehat{h}_v=0.15$, B) $\widehat{h}_v=2.81$. Thin black lines on Delta1 outline the boundaries of the deltaic islands. Thick
 379 black lines in show cross sections displayed in C) and D). C) Proximal cross-section of bed surface and
 380 D) distal cross-section of bed surface.

381
 382 Figures 8 and 9 highlight an interesting effect of vegetation on deltaic systems: for a given
 383 discharge, large $\widehat{h}_v$ decreases sedimentation at the head of the delta while increasing sedimentation at
 384 the fringe. To explore this effect in more detail we delineate different delta portions by upscaling the
 385 shoreline to 105% of the original distance from the center of the river mouth and then downscaling it
 386 every 15% (Fig. 10A). Within each slice shown in Delta 1 (Fig. 10A), we calculate the sediment mass
 387 balance at steady state and then divide it for the total sediment volume coming in the domain from the
 388 river mouth. Fig. 10B shows the amount of sediment ΔSed (kg) deposited or eroded in each slice of
 389 Delta 1 as a function of the distance to the delta head. With larger $\widehat{h}_v$ more sediment is transported to
 390 the edge of the delta where it is could be deposited on distal islands (Fig. 10B).

391
 392 Figure 10. A) Subdivision of the area of Delta 1 in different shoreline-concentric slices. B) Net
 393 sediment deposition (negative means erosion) in each slice for no vegetation, $\widehat{h}_v=0.15$, $\widehat{h}_v=0.52$, and
 394 $\widehat{h}_v=2.81$. Colored lines are interpolations of the calculated points with quadratic polynomials.
 395 Correlation values of the interpolations are showed on color legend.

396

397 **4. Discussion**

398 **4.1 Connection to previous published studies**

399 An important consideration when modeling the effect of vegetation on sediment transport is how to
400 formulate the connection between the vegetation and the flow field. Most commonly the effect of
401 vegetation is introduced in the flow resistance relationship and many formulations have been presented
402 in the recent past. Augustijn et al., (2011) evaluated five different flow formulas derived for submerged
403 vegetation: Klopstra et al., (1997); Stone and Shen, (2002); Baptist et al., (2007); Huthoff et al., (2007);
404 and Yang and Choi, (2010). Each of these models is based on measurable vegetation characteristics to
405 account for flow resistance by vegetation. The evaluation of the five formulas is based on different tests
406 by comparing velocity, water depth, and roughness parameters with experimental data on rigid and
407 flexible vegetation. Augustijn et al., (2011) showed that all models well reproduce experimental data,
408 both for rigid and flexible vegetation.

409 The Baptist formulation we employ in this paper (Baptist, 2005; Baptist et al., 2005; Baptist et al.,
410 2007) has been validated against a range of data. Facchini et al., (2009) and Arboleda et al., (2010)
411 tested and validated the Baptist formula in the presence of different species of vegetation with data on
412 water flow and suspended sediment transport measured, respectively, in Ewijkse Plaat (Netherlands)
413 and Waal river (Netherlands). Baptist et al., (2005) applied his model to the rivers Allier (France),
414 Volga (Russia), and Rhine (Netherlands) showing consistent results. Also, Baptist et al., (2007) applied
415 a genetic algorithm to the results of a 1-DV model, obtaining a roughness expression that exactly
416 matches his analytical expression based on synthetic data. The results of this study were interpreted and
417 evaluated with a comparison with an independent dataset of flume experiments producing a reliable
418 match.

419 Additionally, Crosato and Saleh (2011) provide another validation of the Baptist formulation by
420 studying the effects of floodplain vegetation on river planforms. A 2D morphodynamic model, coupled
421 with a model for flow resistance based on Baptist's formula, was applied to a hypothetical case with
422 the same characteristics of Allier River in France and then compared with field data finding a good
423 correspondence. Crosato and Saleh (2011) found that without vegetation the river develops a braided
424 planform, while in the presence of vegetation all the flow concentrates in a single channel. These
425 results are in agreement with our simulations, showing that high vegetation favors flow concentration
426 (Fig. 8), and sediment bypassing to the distal parts of the delta (Fig. 10).

427 A comparison among different vegetation models presented in Vargas-Luna et al. (2015) indicates
428 that the formulation of Baptist (2005) provides the best estimate for vegetation drag, while the model
429 of Klopstra et al., (1997) better computes the vertical velocity profile. This study also shows that the
430 formulation of Baptist (2005) is excellent at predicting the reduction in bed shear stress in the
431 vegetation layer in the case of submerged vegetation. This is an important result for sediment fluxes,
432 since shear stress at the bed controls sediment entertainment and therefore sediment transport.

433 Schwarz et al., (2014) also used the 2-D depth-averaged Delft3D model with a vegetation drag
434 module based on Baptist (2005). Their goal was to determine whether salt marsh channels form
435 because of preexisting mudflat channels or because of vegetation-induced channel erosion, as indicated
436 by Temmerman et al., (2007). They show that if already present mudflat channels are deep enough,
437 vegetation encroachment does not lead to the formation of new channels, since all the tidal flow is
438 concentrated in the preexisting channels (e.g. Fagherazzi and Furbish, 2001). This result can be applied
439 to vegetation in deltaic islands, suggesting that the presence of incised distributaries is likely hindering
440 the formation of new channels by vegetation-induced erosion. Erosion patterns in Fig. 9A, seems to
441 confirm this hypothesis, with erosion of islands localized at the margins of the distributaries and not in
442 the islands interior, which is largely a depositional environment (Fig. 9 A,B).

443 Here we considered uniform vegetation with constant characteristics (height, density, and diameter)
444 but in a deltaic environment vegetation succession is important, with different vegetation species
445 colonizing the newly emerged land (Johnson et al., 1985). Complex vegetation dynamics (e.g. Kim et
446 al., 2014) can interact with hydrological and sediment transport processes ultimately affecting the
447 wetland landscape (Marani et al., 2013). Future modeling research should address vegetation zonation
448 in deltaic islands.

449 Belliard et al., (2015) studied the formation of tidal channels using the two-dimensional
450 hydrodynamic model WWTM (Defina, 2000; Carniello et al., 2005) coupled to a vegetation module
451 accounting for feedbacks between vegetation and sediment transport processes. Their simulation results
452 indicate that high rates of sediment deposition favor channel development after an initial phase
453 controlled by incision. They further show that vegetation has an important role in channel evolution,
454 with different vegetation species leading to different channel network morphologies. Similar concepts
455 should also be valid for deltaic distributaries, the development of which is clearly driven by
456 sedimentation and delta progradation. Fig. 9 shows that different vegetation surfaces affect erosion and
457 sedimentation in the deltaic islands, with dense vegetation building levees near the distributaries and
458 deflecting water and sediment from the islands near the delta apex toward the distal islands. Vegetated
459 surfaces can therefore control sedimentation patterns in the delta, and therefore the evolution of
460 distributaries similarly to what was found by Belliard et al., (2015). Moreover sediment diverted to the
461 deltaic shoreline by vegetation should favor the extension and deepening of the distributaries.
462 Unfortunately in our model vegetation and landforms are not allowed to co-evolve, since vegetation is
463 introduced only when the delta is already formed. Future research should explore how the feedbacks
464 between vegetation and sediment deposition control the morphodynamics of distributaries and islands
465 during delta progradation.

466 In our model vegetation has a passive role and therefore vegetation dynamics are not simulated.
467 Perucca et al (2006) show that when the vegetation is allowed to co-evolve with river morphology,
468 different distributions of biomass density arise as a function of frequency of river flooding,
469 sedimentation, and position of the water table in the river banks. The resulting spatially and temporally
470 variable vegetation density has an important role in the morphodynamic evolution of the river,
471 influencing, for example, river meandering (Perucca et al., 2007). Moreover, Perucca et al., (2007)
472 indicate that slow vegetation growth can favor erosion, since vegetation does not have time to establish
473 and stabilize the river banks. In the case of a delta, slow vegetation growth would favor deposition near
474 the delta head (Fig. 10), and a steeply sloping delta top. Clearly the inclusion of vegetation dynamics in
475 our model is deemed necessary to understand the temporal evolution of deltaic islands.

476

477 **4.2 Vegetation effect at the small scale versus the large scale**

478 An important vegetation effect is displayed in Fig. 5, showing that the flow on the surface of distal
479 islands first decreases when there is more vegetation on the delta but, for very tall vegetation relative to
480 flow depth, the flow starts increasing again. This result suggests that two competing processes are at
481 play. At the small spatial scale more vegetation augments hydraulic roughness, resulting in a deflection
482 of the water from the islands to the channels. However, at a larger spatial scale, vegetation near the
483 head of the delta forces flow towards the distal islands, because the channelized flow bypasses the
484 islands at the delta head and inundates the vegetated islands at the shoreline. This large-scale effect is
485 significant enough to overcome the deflection effect due to local vegetation, bringing sediments to the
486 distal islands, with potentially important consequences for the long-term evolution of the entire delta
487 (Fig. 10). This dichotomy highlights the importance of spatial gradients in water and suspended
488 sediments, often neglected in ecogeomorphic studies. For example, salt marsh dynamics as a function
489 of sea level rise and sediment availability is often addressed with point models (Fagherazzi et al., 2006;

490 Marani et al., 2007; Kirwan et al., 2010) when in reality the spatial distribution of vegetation and
491 sediment fluxes could lead to salt marsh survival or drowning at different locations within the same
492 coastal system. Similarly, spatially averaged aggradation rates in entire deltaic systems are often
493 compared to rates of sea-level rise to determine vulnerability to flooding (e.g. Syvitski et al., 2009).
494 Such a simplified analysis might not capture the feedbacks between vegetation and sediment fluxes that
495 act at the spatial scale of the entire delta, as indicated by the results presented herein. The importance
496 of the spatial distribution of flow and sediment is particular evident in deltas. In fact deltas are
497 characterized by point sources of discharge (e.g. the incoming rivers) and the redistribution of water
498 and sediment is driven by gradients in water surface and velocity that self-establish within the deltaic
499 system. Vegetation, as shown in this manuscript, massively tampers with these gradients, leading to a
500 complex response that cannot be captured by point models.

501

502 **4.3 Implications for delta resilience**

503 Our results have a significant impact on the resilience of freshwater deltaic marshes in the face of
504 relative sea level rise. Nardin and Edmonds (2014) found that sedimentation is maximized if the flood
505 wave arrives when vegetation has intermediate density and height. This is the optimal condition for
506 accretion so that the delta can counteract relative sea level rise without drowning. Here we underscore
507 the importance of the spatial distribution of sedimentation. Indeed, we observe that as vegetation height
508 and density increase more sediment is deflected into the channels to accumulate at the delta fringe (Fig.
509 8, 9, and 10). In a simplified sense, this would suggest that, all else being equal, vegetated deltas should
510 have shallower top set slopes and larger planform areas (since sediment is preferentially transported to
511 the shoreline) compared to their non-vegetated counterparts. Of course, this assumes the absence of
512 negative feedbacks that dampen this outcome since our experiments were not fully morphodynamic.

513 The effects of vegetation on delta resiliency are not straightforward. Consider that heavily vegetated
514 deltas may be less resilient compared to their less vegetated counterparts. After all, heavily vegetated
515 deltas may have a protective covering of vegetation that stabilizes marsh surfaces, but if our results
516 presented in Fig. 10 are correct, they will have larger areas and lower average elevations, which could
517 make them more susceptible to drowning by relative sea-level rise. On the other hand non-vegetated
518 deltas would have higher average elevations if their surface slopes are indeed steeper, but they will lack
519 the protective covering of vegetation. This underscores the idea that an intermediate relative height is
520 again optimal for resilience, as also indicated in Nardin and Edmonds (2014). Intermediate relative
521 vegetation height will increase sedimentation (Fig. 9) and also provide a stabilizing cover on islands.

522 Our results suggest that deltaic freshwater marshes might behave differently from tidal salt-marshes
523 given that vegetation height and density seemingly have a different impact on hydrodynamics and
524 sediment transport. In a tidal salt marsh, an increase in vegetation biomass always favors sediment
525 deposition and hence marsh resilience against sea level rise (Kirwan et al., 2010; Kirwan and
526 Mengonigal, 2013). In freshwater deltaic marshes, an increase in vegetation height and density has a
527 twofold effect: on one hand it favors trapping of sediment on the islands; on the other hand the increase
528 in roughness deflects water flow and sediment into the channels thus bypassing the marsh surface (Fig.
529 4 and 5). Contrary to tidal salt marshes, our study highlights the fact that under certain conditions an
530 increase in vegetation biomass might reduce the amount of sediment deposited on the marsh islands. In
531 the presence of vegetation we also detect high deposition at the edge of deltaic islands because of the
532 reduced velocities. This deposition gives rise to sandy levees, which would further confine the flow in
533 the channels.

534

535

536

537   **5   Conclusions**

538   Here we have explored how freshwater marshes affect spatial sediment distribution on deltaic
539 islands during a river flooding event. Intermediate vegetation height and density maximizes sediment
540 deposition on the entire delta. Our results indicate that when deltaic islands are colonized with tall,
541 dense vegetation they will deflect water and sediment into the neighboring channels, preferentially
542 transporting water and sediment to the shoreline. This encourages sediment deposition on distal deltaic
543 islands at the expense of islands near the delta apex. Non-vegetated deltas, on the other hand, deposit
544 relatively more sediment at the delta apex compared to the shoreline. A possible outcome of this effect
545 is that non-vegetated deltas will have steeper surface slopes compared to their vegetated counterparts.

546   We suggest that deltas with intermediate vegetation height and densities could be the most
547 resilient. After all, our results here and in other studies (e.g. Nardin and Edmonds, 2014) show this
548 maximizes sedimentation over the delta as a whole. Furthermore, intermediate vegetation height and
549 density will reduce the surface slope of the delta (compared to a non-vegetated delta). If vegetation
550 height and density are too high, sediment is delivered to the delta shoreline producing a flat, extended
551 delta with lower elevations that is more prone to drowning. Therefore freshwater deltaic marshes show
552 different sediment dynamics with respect to salt marshes. Sedimentation is not directly proportional to
553 vegetation height and density but there is an optimum that can maximize sediment deposition.

554   Finally, vegetation can affect deltaic hydrodynamics and morphodynamics at different spatial
555 scales. At the small scale, vegetation on islands deflects water and sediment fluxes in nearby channels.
556 At the scale of the entire delta, vegetation favors flow bypass at the delta head while promoting the
557 flooding of the distal islands. This dual effect highlights the need to use spatially distributed models to
558 assess the morphodynamic evolution and resilience of deltaic systems.

559

560

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566

567

Run ID	Delta	Q_i (m^3s^{-1})	h_v (m)	n (m^{-1})	Run ID	Delta	Q_i (m^3s^{-1})	h_v (m)	n (m^{-1})
R1111	1	2,500	0.00	0.50	R1182	1	2,500	1.00	0.10
R1121	1	2,500	0.05	0.50	R1192	1	2,500	1.50	0.10
R1131	1	2,500	0.10	0.50	R1222	1	3,750	0.05	0.10
R1141	1	2,500	0.15	0.50	R1232	1	3,750	0.10	0.10
R1151	1	2,500	0.20	0.50	R1242	1	3,750	0.15	0.10
R1161	1	2,500	0.50	0.50	R1252	1	3,750	0.20	0.10
R1171	1	2,500	0.80	0.50	R1262	1	3,750	0.50	0.10
R1181	1	2,500	1.00	0.50	R1272	1	3,750	0.80	0.10
R1191	1	2,500	1.50	0.50	R1282	1	3,750	1.00	0.10
R2111	2	2,500	0.00	0.50	R1292	1	3,750	1.50	0.10
R2121	2	2,500	0.05	0.50	R1322	1	5,000	0.05	0.10
R2131	2	2,500	0.10	0.50	R1332	1	5,000	0.10	0.10
R2141	2	2,500	0.15	0.50	R1342	1	5,000	0.15	0.10
R2151	2	2,500	0.20	0.50	R1352	1	5,000	0.20	0.10
R2161	2	2,500	0.50	0.50	R1362	1	5,000	0.50	0.10
R2171	2	2,500	0.80	0.50	R1372	1	5,000	0.80	0.10
R2181	2	2,500	1.00	0.50	R1382	1	5,000	1.00	0.10
R2191	2	2,500	1.50	0.50	R1392	1	5,000	1.50	0.10
R3111	3	2,500	0.00	0.50	R1123	1	2,500	0.05	0.05
R3121	3	2,500	0.05	0.50	R1133	1	2,500	0.10	0.05
R3131	3	2,500	0.10	0.50	R1143	1	2,500	0.15	0.05
R3141	3	2,500	0.15	0.50	R1153	1	2,500	0.20	0.05
R3151	3	2,500	0.20	0.50	R1163	1	2,500	0.50	0.05
R3161	3	2,500	0.50	0.50	R1173	1	2,500	0.80	0.05
R3171	3	2,500	0.80	0.50	R1183	1	2,500	1.00	0.05
R3181	3	2,500	1.00	0.50	R1193	1	2,500	1.50	0.05
R3191	3	2,500	1.50	0.50	R1223	1	3,750	0.05	0.05
R1211	1	3,750	0.00	0.50	R1233	1	3,750	0.10	0.05
R1221	1	3,750	0.05	0.50	R1243	1	3,750	0.15	0.05
R1231	1	3,750	0.10	0.50	R1253	1	3,750	0.20	0.05
R1241	1	3,750	0.15	0.50	R1263	1	3,750	0.50	0.05
R1251	1	3,750	0.20	0.50	R1273	1	3,750	0.80	0.05
R1261	1	3,750	0.50	0.50	R1283	1	3,750	1.00	0.05
R1271	1	3,750	0.80	0.50	R1293	1	3,750	1.50	0.05

R1281	1	3,750	1.00	0.50	R1323	1	5,000	0.05	0.05
R1291	1	3,750	1.50	0.50	R1333	1	5,000	0.10	0.05
R1311	1	5,000	0.00	0.50	R1343	1	5,000	0.15	0.05
R1321	1	5,000	0.05	0.50	R1353	1	5,000	0.20	0.05
R1331	1	5,000	0.10	0.50	R1363	1	5,000	0.50	0.05
R1341	1	5,000	0.15	0.50	R1373	1	5,000	0.80	0.05
R1351	1	5,000	0.20	0.50	R1383	1	5,000	1.00	0.05
R1361	1	5,000	0.50	0.50	R1393	1	5,000	1.50	0.05
R1371	1	5,000	0.80	0.50	R3123	3	2,500	0.05	0.05
R1381	1	5,000	1.00	0.50	R3133	3	2,500	0.10	0.05
R1391	1	5,000	1.50	0.50	R3143	3	2,500	0.15	0.05
R1122	1	2,500	0.05	0.10	R3153	3	2,500	0.20	0.05
R1132	1	2,500	0.10	0.10	R3163	3	2,500	0.50	0.05
R1142	1	2,500	0.15	0.10	R3173	3	2,500	0.80	0.05
R1152	1	2,500	0.20	0.10	R3183	3	2,500	1.00	0.05
R1162	1	2,500	0.50	0.10	R3193	3	2,500	1.50	0.05
R1172	1	2,500	0.80	0.10					

568 Table 1. Model parameters for modeling experiments used in this study.

569

570 **Notation**

571 C_b alluvial bed roughness according with to Chezy, $m^{1/2} s^{-1}$;

572 C'_b effective bed roughness under vegetation according with to Chezy, $m^{1/2} s^{-1}$;

573 C_D drag coefficient, -;

574 C_{rs} representative Chezy value for vegetation totally submerged, $m^{1/2} s^{-1}$;

575 C_r representative Chezy value for vegetation partially submerged, $m^{1/2} s^{-1}$;

576 c_{eq} equilibrium sediment concentration, $kg m^{-3}$;

577 D stems diameter, m;

578 D_{50} sediment median grain size, μm ;

579 $\overline{D_v}$ averaged water depth with vegetation, m;

580 $\overline{D_{nv}}$ averaged water depth without vegetation, m;

581 $\overline{U_v}$ averaged water velocity with vegetation, ms^{-1} ;

582 $\overline{U_{nv}}$ averaged water velocity without vegetation, ms^{-1} ;

583 f_s reduction factor for vegetation totally submerged, -;

584 f_{ns} reduction factor for vegetation partially submerged, -;

585 Q_i river discharge, m^3s^{-1} ;

586 Q_{si} in-coming sediment flux, kg s^{-1} ;

587 Q_{so} out-coming sediment flux, kg s^{-1} ;

588 q water flux, m^3s^{-1} ;

589 m number of stems for square meter, m^{-2} ;

590 n vegetation density, m^{-1} ;

591 c suspended sediment mass concentration, kg m^{-3} ;

592 g gravitational acceleration, m s^{-2} ;

593 h water depth, m;

594 h_v vegetation height, m;

595 $\hat{h}_v$ non dimensional vegetation height, m;

596 i slope, -;

597 k van Karman constant, -;

598 R_W water flux ratio, -;

599 R_U water velocity ratio, -;

600 R_D water depth ratio, -;

601 F_B water flux computed by *Delft3D* on deltaic islands, m^3s^{-1} ;

602 $F_{B_{noveg}}$ water flux computed by *Delft3D* on non-vegetated deltaic islands, m^3s^{-1} ;

603 F_W normalized water flux computed by *Delft3D* on deltaic islands, -;

604 η elevation of the water surface, m;

605 t time, s;

606 $\bar{u}$ depth averaged flow velocity, m s^{-1} ;

607 u_u flow velocity above vegetation, m s^{-1} ;

608 u_v flow velocity inside vegetation, m s^{-1} ;

609 U time averaged x-direct fluid velocity, m s^{-1} ;

610 V time averaged y-direct fluid velocity, m s^{-1} ;

611 x, y planform directions, m ;

612 Δs_{ed} sediment trapped in Delta slice, kg ;

613 ρ fluid density, kg m^{-3} ;

614 τ_b bed shear stress, N m^{-2} ;

615 T_S adaptation time, s ;

616 $\hat{\tau}_{ch}$ mean channels shear stress, N m^{-2} ;

617 $\hat{\tau}_{bar}$ mean island shear stress, N m^{-2} ;

618 $|\hat{\tau}_{ch}|_v$ mean channels shear stress with vegetation, N m^{-2} ;

619 $|\hat{\tau}_{ch}|_{nv}$ mean channels shear stress without vegetation, N m^{-2} ;

620 $|\hat{\tau}_{bar}|_v$ mean channels shear stress with vegetation, N m^{-2} ;

621 $|\hat{\tau}_{bar}|_{nv}$ mean channels shear stress without vegetation, N m^{-2} ;

622 τ_{bv} bed shear stress in presence of vegetation totally submerged, N m^{-2} ;

623 $\tau_{bv,ns}$ bed shear stress in presence of vegetation partially submerged, N m^{-2} ;

624 τ_v shear stress due to the vegetation drag, N m^{-2} ;

625 τ_t total shear stress, N m^{-2} ;

626 ν_H horizontal eddy viscosity, $\text{m}^2 \text{s}^{-1}$;

627 ν_V vertical eddy viscosity, $\text{m}^2 \text{s}^{-1}$;

628 $\varepsilon_{S,x}, \varepsilon_{S,y}, \varepsilon_{S,z}$ sediment eddy diffusivity along three coordinate axis directions, $\text{m}^2 \text{s}^{-1}$;

629

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