Sensitivity of estuary hydrodynamics to vegetation parameterisation

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5 authors, including:

Thomas van Veelen
University of Twente

Harshinie Karunarathna
Swansea University

William Bennett
Swansea University

Tom Fairchild
Swansea University

Sensitivity of estuary hydrodynamics to vegetation parameterisation

By Thomas J. van Veelen, Harshinie Karunarathna, William G. Bennett, Tom P. Fairchild & Dominic E. Reeve

Zienkiewicz Centre for Computational Engineering, Swansea University, SA1 8EN, UK

Abstract

Salt marshes are coastal wetlands that can reduce flood risk by their vegetation. The drag that salt marsh plants induces on currents modifies estuary hydrodynamics which affects flood water levels, surge propagation and sediment transport. Four parameterisations to model the drag by vegetation on currents have been proposed in literature: (i) a fixed bed roughness, (ii) a depth- dependent bed roughness, (iii) a trachytope model, and (iv) a momentum sink term. Yet, it is unclear how sensitive modelled estuary hydrodynamics are to the selection of a parameterisation. Here, we compare the flow-vegetation interaction under each parameterisation against each other and a reference case without vegetation for an idealised funnel-shaped estuary. We find that depth-averaged flow velocities are reduced over salt marshes due to the presence of vegetation under all parameterisations, but the velocity structure, turbulence, drainage time of flooded areas and bed shear stress are sensitive to the selected parameterisation. The vertical velocity profile under a momentum sink term best resembles the theoretical structure that is established in literature. Furthermore, a parameterisation via bed roughness results in high bed shear stress which are important for modelling sediment transport. Our results highlight the importance of adequately resolving the flow-vegetation interface in flood risk models as estuary hydrodynamics are sensitive to parameterisations of vegetation.

1. Introduction

Salt marshes are intertidal coastal wetlands that form green buffer zones between land and sea. They are frequently found in sheltered areas such as estuaries in temperate climate zones (Allen 2000). Salt marshes exhibit salt-tolerant vegetation that alleviates coastal flood risk. The additional drag generated by vegetation attenuates currents and waves, lowers flood water levels and can expand sediment budget (Bouma *et al.* 2014; Leonardi *et al.* 2018; Mullarney & Henderson 2018). Additionally, they provide co-benefits such as carbon storage, grazing area for cattle, ecosystem enhancement and recreational opportunities (Sutton-Grier *et al.* 2015).

The interaction between currents and vegetation is key for sediment accretion and storm surge attenuation over salt marshes. As salt marshes are located in the intertidal zone, they are subjected ebb and flood tidal flows. The tide carries sediments which are essential for the sediment budget on the vegetated platforms and its function as a coastal buffer zone. Furthermore, the momentum lost by drag force balances the forcing by the pressure gradient, which can reduce storm surge levels over longer distances (Zhang *et al.* 2012). Therefore, modelling flow patterns over salt marshes is important to investigate their function as a natural flood defence.

Current fields over salt marshes are typically solved using numerical models for which four parameterisations have been proposed. Under the first parameterisation, drag by vegetation is modelled via an increased bottom roughness coefficient for vegetated areas (e.g. Mariotti & Canestrelli 2017). Second, Baptist *et al.* (2007) noted that a fixed bottom roughness cannot account for variations in drag force due to changes in water level, which affect the part of the water column that is populated by vegetation. Therefore, they formulated a depth-dependent bottom roughness, which has been successfully applied for vegetated channel flow (e.g. Verschoren *et al.* 2016), but may overestimate bed shear stress (Hu *et al.* 2015). As a numerical solution, it has been proposed to consider vegetation a roughness element but include it partially as a sink term in the momentum balance. Finally, vegetation is considered a rigid cylindrical object in the water column that generates drag and turbulent energy over its length, where the drag fully implemented as a sink term in the momentum balance (e.g. Temmerman *et al.* 2005).

The four parameterisations have been applied successfully in separate studies with aquatic vegetation but there is limited insight in the sensitivity of modelled hydrodynamics to the selected parameterisations. Ashall *et al.* (2016) compared parameterisations via bottom friction and momentum sink over rigid cylinders for a large macro-tidal estuary. They found that both parameterisations reproduced current magnitudes for most of the tidal cycle, but the dynamics under submerged vegetation could only be captured via a momentum sink term over rigid cylinders. Alternatively, Al-Asadi & Duan (2017) found that a plant submergence term in bed roughness formulations was key to reproduce velocities on freshwater marshes. As both studies focussed on reproducing currents under specific field site conditions and selected parameterisations, our understanding of the sensitivity of all parameterisations towards wider estuarine hydrodynamics is limited.

In this study, we set up a model of an idealised estuary to investigate the impact of the four parameterisations of drag by vegetation on hydrodynamics. Rather than the reproducing field site conditions, our interest lies in the qualitative impact of the modelling parameterisation on hydrodynamic parameters, such as current velocity, velocity structure, turbulence and water level. Understanding of the model sensitivity in these areas can improve our understanding of the sensitivity of flood risk models in general.

2. Model set up

2.1. *Model description*

Modelling suite The computational coastal and river model Delft3D (Lesser *et al.* 2004) was selected to investigate the interaction between vegetation and tidal currents. Delft3D uses a finite-difference scheme to numerically solve the horizontal momentum equation. It calculates water levels, currents and turbulence based on forcing at the boundary (e.g. tides and river flow). It is an open source software package and includes different parameterisations for modelling vegetation. The modelling suite has been successfully applied to model hydrodynamics over salt marshes in two and three dimensions (e.g. Ashall *et al.* 2016; Wu *et al.* 2017).

Model domain Our model represents an idealised funnel-shaped estuary with back-barrier salt marshes (Fig. 1) which is a common estuary type in Northwest Europe (Allen 2000). The estuary is 2000m in length and 1000m in width and connects to a sea inlet at the mouth and a river at the head. The river dynamics are modelled up to the tidal limit, which is 3000m beyond the head of the estuary. Furthermore, a channel runs along the central axis of the estuary and connects to the sea and the river. Its cross-section is triangular with a minimum bed level of 2.5 m below mean sea level at the mouth and 1.5 m below mean sea level at the head. The width of the channel decreases linearly

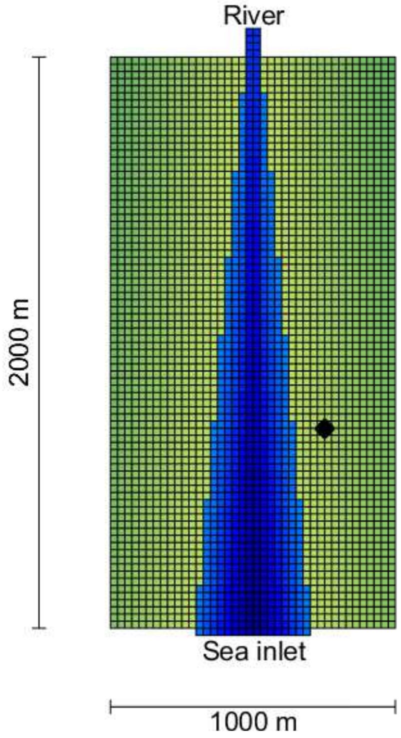

Figure 1. The model domain which represents a funnel-shaped estuary with back-barrier marshes. Blue grid cells denote the channel and green cells denote salt marshes. the river continues 3km outside the displayed area. Finally, the black diamond denotes a model output comparison location.

from 600m at the mouth to 50m at the head. The remaining area is covered by salt marshes with a uniform vegetation cover. They are on an uphill slope of 2×10^{-3} m/m in cross-estuary direction (channel to land) and 1.25×10^{-4} in along-channel direction (mouth to head). The marsh elevation is 0.8 m above mean sea level at the channel edge and between 1.25 m (mouth) and 1.5 m (head) at its landward edge. The vegetation is inspired by common salt marsh shrub Atriplex Portulacoides with height $h_v = 300$ mm, stem diameter $b_v = 2.5$ mm and stem density $n_v = 2000$ stems/m^2.

The model domain is represented by a rectangular grid of $25{\times}25$ m cells with refinement around the central axis of the estuary. The deeper channel and river are projected on a $10{\times}25$ m grid (cross-estuary×along-estuary) due to high expected flow velocities along this axis. The grid has been extended towards the sea by 500 m at the mouth to create a relaxation zone between the boundary and the area of interest. We run the model both in depth-averaged and in three dimensional modes. For the latter case, the model is expanded to 50 vertical layers which adjust with water depth.

Boundary conditions We model a tide-dominated estuary for which we assume that the effect of river inflow on the hydrodynamics is negligible. We apply an M_2-tide with amplitude 1.5 m on the seaward boundary. The tidal amplitude has been selected to fully inundate the salt marshes. The highest tidal level exceeds the salt marsh elevation by 0.7 m at its seaward edge and matches the bottom elevation at the landward edge. Under these conditions, the flow-vegetation interaction is modelled for submergence depths across the salt marsh.

Time frame The model is run for two and a half tidal cycles. The first one and a half cycle act as a spin-up and the final cycle is used to study the dynamics. Sensitivity testing showed that tidal dynamics did not change when the model was run for more cycles. The time step is 3 s.

2.2. *Vegetation parameterisation*

We test the effect of vegetation on currents under four parameterisations. Parameters have been selected such that similar drag is generated under each parameterisation.

Fixed bed roughness The drag by vegetation is implemented via a rougher bed in vegetated areas compared to non-vegetated areas. Our model describes bed roughness by a Chézy coefficient. We set $C = 7$ m$^{1/2}$/s such that the drag generated is in the same order as the depth-dependent roughness for the range of inundation depths on the salt marshes. The bed roughness is set at $C_b = 65$ m$^{1/2}$/s for non-vegetated areas (Marciano *et al.* 2015).

Water depth-dependent bed roughness Baptist *et al.* (2007) proposed a formulation in which the effective bottom drag is function of vegetation height h_v and water depth h. They distinguished between flow through emergent ($h < h_v$) and over submerged vegetation ($h > h_v$). If vegetation is emergent, the flow resistance is assumed constant over the water column and depends on the frontal area of the vegetation, which is estimated under the assumption of rigid cylindrical stems. If vegetation is submerged, the velocity profile is divided in two parts: (1) the vegetated zone, where the emergent velocity profile is applied and (2) the free flow zone, where a logarithmic velocity profile is applied. The equivalent Chézy coefficient is defined as

$$\begin{aligned} C(t) &= \sqrt{\frac{1}{1/C_b^2 + C_D n_v b_v h/(2g)}} && \text{if } h < h_v \\ C(t) &= \sqrt{\frac{1}{1/C_b^2 + C_D n_v b_v h_v/(2g)}} + \frac{\sqrt{g}}{\kappa} \ln\left(\frac{h}{h_v}\right) && \text{if } h > h_v \end{aligned} \tag{2.1}$$

Herein, $C_D = 1$ is the dimensionless drag coefficient (Tanino & Nepf 2008), $g = 9.81$ m/s^2 is the gravitational acceleration and $\kappa = 0.41$ is the von Kármán constant. The Chézy coefficient is updated every time step in accordance with local water depth.

Trachytope model The trachytope model considers vegetation a bottom roughness element, but implements partially implements its effect as a momentum sink term (Al-Asadi & Duan 2017). The effect of vegetation on flow is partially modelled via Chézy roughness

$$\begin{aligned} C(t) &= C_b && \text{if } h < h_v \\ C(t) &= C_b + \frac{\sqrt{g}}{\kappa} \ln\left(\frac{h}{h_v}\right) \sqrt{\frac{1}{C_D n_v b_v h_v/(2g)}} && \text{if } h > h_v \end{aligned} \tag{2.2}$$

and partially via a sink term in the momentum equations $-\frac{\lambda}{2}\boldsymbol{u}^2$ in which

$$\begin{aligned} \lambda(t) &= C_D b_v n_v && \text{if } h < h_v \\ \lambda(t) &= C_D b_v n_v + \frac{h}{h_v}\frac{c_b^2}{C^2} && \text{if } h > h_v \end{aligned} \tag{2.3}$$

and $\boldsymbol{u} = (u, v, w)$ is the flow velocity. The combined roughness via bottom friction (Eq.

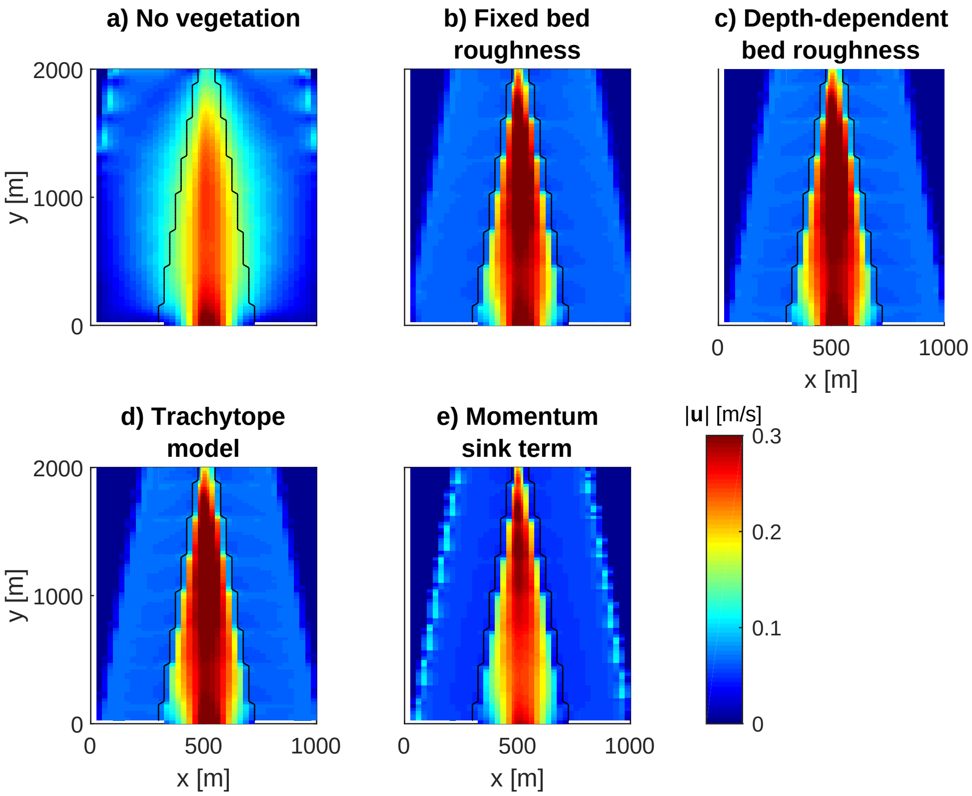

FIGURE 2. Depth averaged flow velocity magnitude at peak flood currents (40 minutes before high water) under five model set ups: a) no vegetation, b) fixed bed roughness, c) depth-dependent bed roughness, d) trachytope model, and e) momentum sink term. The black contour denotes the edge of the salt marsh.

2.2) and momentum (Eq. 2.3) is equivalent to water depth-dependent bed roughness (Eq. 2.1) and have been defined such that the ratio $\boldsymbol{u}/C^2$ remains constant when the water level rises or falls (Deltares 2018). The available implementation in Delft3D includes the momentum sink term in the depth-averaged momentum equations in a depth-averaged model or in the top layer of a 3D model.

Momentum sink term Delft3D includes a vegetation model in which the drag by vegetation is included as a sink term in the momentum equations. Plant morphology is simplified to rigid cylindrical stems. As currents flow around vegetation, momentum is lost due to drag force

$$\boldsymbol{F}(z,t) = \frac{1}{2}\rho C_D b_v n_v |\boldsymbol{u}|\boldsymbol{u}. \tag{2.4}$$

Herein, $\rho = 1025$ kg/m^3 is the density of seawater. The drag force is a function of the vertical position in the water column z such that drag is only exerted over the height of the vegetation. Drag coefficient $C_D = 1$ matches the depth-dependent bed roughness parameterisation. Finally, the work done by the drag force is implemented as turbulence source term in the k-ϵ turbulence closure model in Delft3D (Uittenbogaard & Klopman 2001).

In addition to the four vegetation formulations, we also run the model without vegeta-

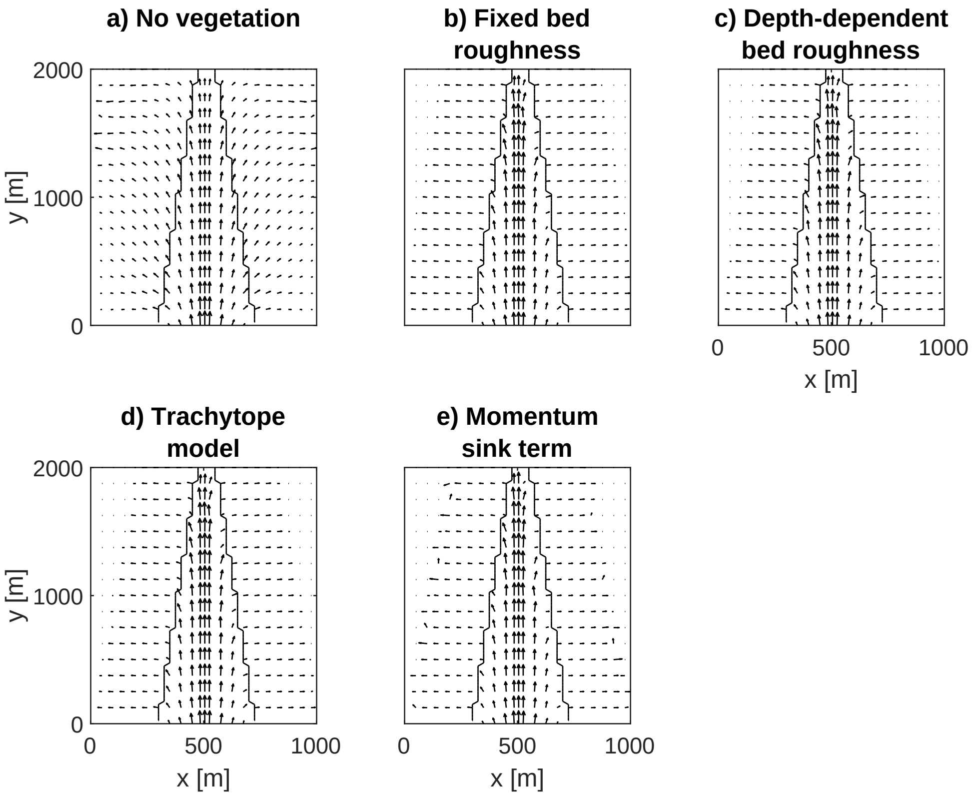

FIGURE 3. Direction of depth averaged flow velocities at peak flood currents (40 minutes before high water) under five model set ups: a) no vegetation, b) fixed bed roughness, c) depth-dependent bed roughness, d) trachytope model, and e) momentum sink term. The black contour denotes the edge of the salt marsh.

tion cover. The no vegetation model has the same morphology as the parameterisations with vegetation and the bottom roughness equals the bed roughness $C = 65\ \mathrm{m}^{1/2}/\mathrm{s}$ over the full domain.

3. Results

3.1. *Depth-averaged modelling*

Based on our depth-averaged model runs, we find that vegetation has significant impact on the current magnitude and direction on the salt marshes and in the main estuary channel. The results are presented shortly after peak flood at 40 min before high water when most of the salt marsh area is inundated and current velocities are high. The results under ebb flow were similar to those under flood flow.

Salt marshes contribute to flow concentration through the main estuary channel under peak flood currents (Fig. 2). When vegetation is absent, current velocities decrease at increasing distance from the central axis of the estuary as water depths become shallower and velocities gradually change from channel to salt marsh. When vegetation is present, there is a clear distinction between the high velocities in the main channel and the low velocities over the salt marsh. The velocities over the salt marsh are lower compared to the reference case without vegetation due to additional drag by the vegetation. Conversely, the velocities in the channel have increased as flow concentrates in the main channel. The effects of vegetation are qualitatively similar under all four vegetation parameterisations but velocities are slightly lower under the momentum sink term on the salt marshes and in the channel.

The directions of flood currents supports the channelling effect of vegetation (Fig. 3). The flood currents are directed to the northwest and northeast in the reference case without vegetation, which shows that flow partly moves in along-channel direction. Yet, the current direction is strictly in cross-channel direction when vegetation is present under all four vegetation parameterisations. These flow patterns resemble flooding of salt marsh platforms from a direction perpendicular to the nearest creek as was found in prior modelling studies (e.g. Temmerman *et al.* 2005; Ashall *et al.* (2016); Wu *et al.* 2017). As vegetated salt marshes flood from a direction perpendicular to the main channel, the volume of water that passes through the main channel increases which supports modelling results of increased current velocities through the main channel when vegetation is present.

3.2. *3D modelling*

Our three-dimensional model runs show that the vertical structure of horizontal velocity, turbulence, water level and bed shear stress are sensitive to vegetation parameterisation. The model outputs are presented at a location central in the salt marshes where vegetation is fully submerged (Fig. 1). The vertical profiles of velocity and turbulent energy are presented at 40 min before still high water and the time series of water level and bed shear stress are evaluated for the full period that the salt marsh is inundated.

The vertical profiles of horizontal velocity and turbulent energy differ strongly between the four vegetation parameterisations (Fig. 4). The two implementations via bed roughness (fixed roughness and depth-dependent roughness) result in near zero current velocities at the bed and increase logarithmically over the water column. This drives strong turbulence directly above the bed. Alternatively, the trachytope model displays a parabolic velocity profile over the water column with a bed velocity that is similar to the reference model without vegetation. The reduced velocity near the free surface follows from the momentum sink that is implemented in the top layer. The turbulence generated over the water column is comparable to the reference model without vegetation over the full water column. Finally, the velocity and turbulence profiles under the momentum sink term relate to the height of the vegetation as it is only implemented fur the part of the water column that is covered by plants. The velocity within the vegetation is constant over its height and increases in the free flow zone above the vegetation. Furthermore, the turbulent energy is maximal directly above the vegetation canopy.

Salt marsh vegetation may delay the drainage of flooded salt marshes, but results are sensitive to the parameterisation of vegetation (Fig. 5a). The two bed roughness and the momentum sink term parameterisations show that the drainage of salt marshes during ebb tide is delayed by approximately 60 minutes when vegetation is present. The longest delays are modelled by the momentum sink term parameterisation as the free flow layer over vegetation disappears late in the tidal cycle and flow velocities are reduced over the full water column. Conversely, the water level modelled under the trachytope parameterisation is similar to the reference case without vegetation.

Modelled bed shear stresses show that they are sensitive to parameterisations of drag by vegetation via a bed roughness coefficient (Fig. 5b). As bed shear stress is a function of bottom roughness, the bed shear stress modelled by the two bed roughness parameterisations are up to ten times higher than those modelled by the trachytope model, the momentum sink term and the reference case without vegetation. Furthermore, the bed

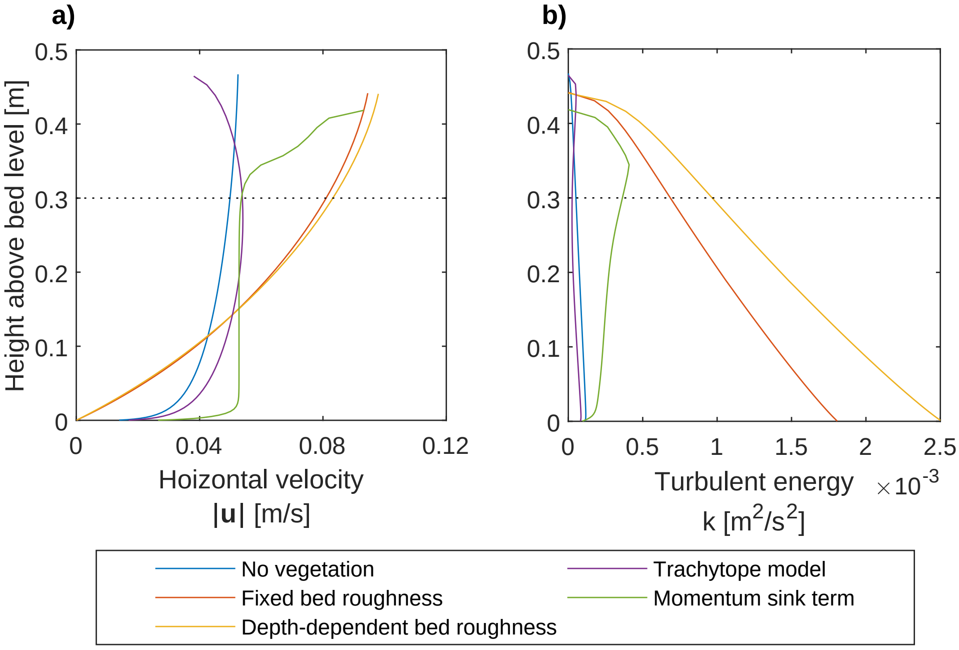

FIGURE 4. Vertical distribution of (a) flow velocity magnitude and (b) turbulent energy on the salt marsh at peak flood currents (40 minutes before high water) under five model set ups. The dotted black line denotes the height of the vegetation.

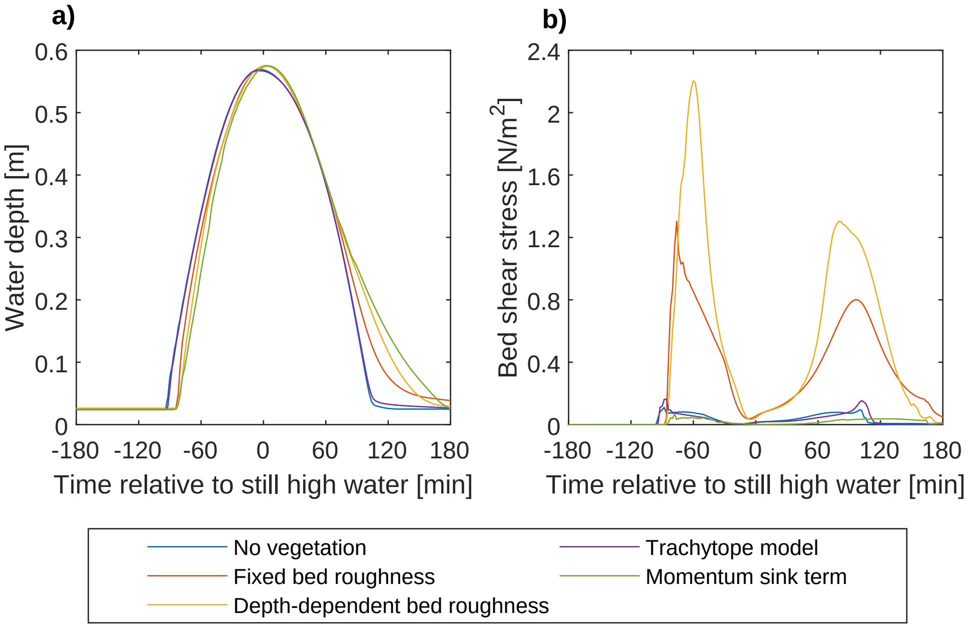

FIGURE 5. Time series of (a) water level and (b) bed shear stress on the salt marsh under five model set ups.

shear stress modelled by the momentum sink term is lower than the trachytope model during the ebb tide as the marsh is drained more gradually under the former model.

4. Comparison of vegetation parameterisations

Though the effect of the four vegetation parameterisations on depth-averaged velocities is qualitatively similar, the velocity structure, turbulence, water level and bed shear stress are sensitive to the parameterisation. The fixed and depth-dependent bed roughness parameterisations result in comparable hydrodynamic parameters but generate high turbulence and shear stresses at the bed. The depth-dependent bed roughness includes a plant submergence term but its impact on investigated parameters is small. Both show the steepest gradient in vertical velocity profile over the water column and the highest shear stresses and turbulent energy at the bed of the four parameterisations studied here.

The trachytope model reduces bed shear stress by partly implementing drag by vegetation via the momentum balance. However, as the drag by vegetation is split over the bed roughness coefficient and a sink term in the momentum balance to tune the bed shear stress exactly, the velocity profile attains a parabolic shape for which no evidence was found in experimental studies. Furthermore, it is the only parameterisation in which drainage of the marsh is not modified by the presence of vegetation.

The momentum sink term is the only parameterisation where the vertical velocity profile is linked to the height of vegetation with a constant velocity inside the vegetation and a free flow zone above the vegetation. This profile closely resembles theoretical descriptions and experimental results (Baptist *et al.* 2007; Nepf 2012). Furthermore, the peak in turbulent energy directly above the canopy of the vegetation has also been described in literature (e.g. Nepf 2012).

Based on our model results, we find that the hydrodynamics are sensitive to the parameterisation of vegetation when considered in three dimensions. Although the idealised model results cannot be validated by observations, the velocity profile as produced by the momentum sink term finds most support in literature. Furthermore, modelling vegetation as objects that generate drag over section of the water column fits the real world situation better than a rough bottom. The sensitivity in hydrodynamic parameters show that the increased physical representation of vegetation in the momentum sink term outweighs its downside as a more complex model. This argument may not hold for depth-averaged modelling when the vertical variations in velocity and turbulence are not included.

5. Conclusions

Salt marsh vegetation modifies the hydrodynamics in estuaries, which is important for flood risk. Here, we have studied the sensitivity of hydrodynamics to parameterisations of vegetation in numerical models. We have set up a model of an idealised estuary in which we have included four parameterisations: (i) fixed bed roughness, (ii) water depth-dependent bed roughness, (iii) trachytope model, and (iv) momentum sink term.

Our model results show that the magnitude of depth-averaged flow velocity and direction are not sensitive to the parameterisations but the vertical structure of horizontal velocity, turbulence, water level and bed shear stress are sensitive to the parameterisation of vegetation. The vertical profile of velocity as modelled via a momentum sink term best resembles literature and prior experimental studies. Conversely, parameterisations via bottom roughness predict high bed shear stresses and the trachytope model generated a parabolic velocity profile for which we found no basis in literature. As estuary hydrodynamics are sensitive to vegetation parameterisations, it is important to adequately model the flow-vegetation interaction by including the key physics.

Our results are important for modelling flood risks as vegetation can modify current magnitudes, flow direction and drainage time of flooded areas. Model results over all parameterisations showed a reduction of current velocities over salt marshes and an increases in flow velocities through the main estuary channel. Furthermore, vegetation prevents along-channel flow over salt marshes. Finally, three out of four model set ups showed that vegetation increased the drainage time of flooded area.

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