



Simulating vegetation effects on flows in 3D using an unstructured grid model: model development and validation

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Received: 26 June 2019 / Accepted: 28 November 2019
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Abstract

Prevalence of vegetation (either submerged or emergent) in shallow water significantly affects the flow and turbulence structure in this environment. In this paper, we develop a new 3D unstructured grid hydrostatic model that accounts for the 3D effects of vegetation on flows. The model uses a semi-implicit time stepping method and treats the new vegetation-related terms implicitly to enhance numerical stability, so the time step does not need to be reduced as compared with the no-vegetation cases. The stability is also independent of the vegetation parameters, so as to efficiently account for large shear that can occur around the canopy. We validate the model using lab data before applying it to a field study in San Francisco Bay-Delta to illustrate the influence of the vegetation on the flow structure as well as tidal energetics. The efficiency of the model enabled by the implicit method allows, for the first time, the simulation of the vegetation effects during multi-year evolution of vegetation in full three dimensions at large spatial scales.

Keywords Vegetation · SCHISM · San Francisco Bay & Delta, USA

1 Introduction

Aquatic vegetation plays a significant role in near-shore hydrodynamics in many rivers, lakes, estuaries, and coastal areas (Brookes and Shields 1996). By impeding currents and attenuating waves, vegetation is observed to play a valuable role in shoreline stabilization and coastal protection which has been an increasing concern in many areas threatened by sea-level rise and climate change (Knutson et al. 1982; Swann 2008; Gedan et al. 2011; Sutton-Grier et al. 2015). Patches of vegetation often redirect the flow field, while helping to trap suspended sediment. Through this process, vegetation has been shown to alter hydrodynamics to the extent that it often governs the geomorphology of its environment in kelp forests (Gaylord et al. 2003), tidal marshes (D'Alpaos et al. 2007;

Temmerman et al. 2005; Möller et al. 2014; Castagno et al. 2018; Nardin et al. 2018), mangrove forests (Horstman et al. 2014), and river systems (Camporeale et al. 2013; Lera et al. 2019). Similarly, in lakes and wetlands, the presence and distribution of vegetation can affect circulation patterns throughout the body of water with significant ecological implications (Da Paz et al. 2005; Kiss and Jozsa 2014). Improving and applying our understanding of the dynamic interaction of vegetation and hydrodynamics is an important process for the sustainable management of our water resources.

In this paper, we will only focus on the vegetation effects on mean flow (i.e., not waves). Flow or current can be impeded or diverted by aquatic plants. Emergent vegetation like near-shore reeds diverts flow laterally around the vegetation (Bennett et al. 2002). Flow through emergent vegetation is largely governed by a balance of pressure gradients and vegetation drag with small length-scale turbulence produced by vegetation wakes (Nepf 1999; Nepf and Vivoni 2000). In contrast, submerged vegetation such as seagrass tends to divert flow vertically above the canopy. Flow past submerged vegetation forms a shear layer at the vegetation canopy surface where turbulence intensity and Reynold's stress are the highest (Nepf and Vivoni 2000; Shimizu and Tsujimoto 1994 (ST94 hereafter)). The shear-induced turbulence causes significant increases in the vertical transport of momentum and nutrients into the vegetation layer (Nepf and Vivoni

Responsible Editor: Eric Deleersnijder

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2000; Ghisalberti and Nepf 2002). The form drag of vegetation on currents is commonly modeled by applying clusters of rigid vertical cylinders in vegetated areas (ST94; Lopez and García 2001; Fischer-Antze et al. 2001). Under this framework, the Reynold's Averaged Navier-Stokes (RANS) equations are solved with an additional form drag term in the mean flow momentum equations and drag-induced turbulence production terms in the turbulence closure equations (which can account for turbulences generated by either emergent or submerged vegetation; cf. Eqs. (7) and (8)). This methodology has been validated with flume data for numerous cases of both emergent and submerged vegetation with varying vegetation submergence ratios, densities, and velocities areas (ST94; Lopez and García 2001; Fischer-Antze et al. 2001; Lowe et al. 2005; Li and Yan 2007). Further modeling efforts that account for the swaying of flexible vegetation have been developed by Dijkstra and Uittenbogaard (2010) and Li and Xie (2011) but the application has been largely limited to laboratory flume studies. Alternatively, the bending effects can also be approximately simulated using a vertically variable drag coefficient as measured by Nepf and Vivoni (2000).

Capturing the hydrodynamic effects of vegetation in natural systems presents many numerical challenges. Vegetated ecosystems are typically patchy and can span large areas with widely variable bathymetry and shorelines. Resolving the spatial details of a natural system, while spanning the time scales at which processes occur is computationally costly. A common way of modeling the effects of vegetation drag on currents is simply applying an increased Manning coefficient in a 2D model; this approach neglects important 3D effects such as differences between submerged and emergent vegetation on momentum (Lapetina and Sheng 2014). A few 3D models have been developed to account for vegetation in natural environments (Temmerman et al. 2005; Horstman et al. 2014; Jin et al. 2007; Kombiadou et al. 2014; Beudin et al. 2017b); however, these models use rectangular or curvilinear grids and explicit time stepping approach, thus severely limiting their applicability for field-scale applications. The irregular and patchy distribution of vegetation in natural habitats is often difficult to resolve efficiently using such meshes. On the other hand, unstructured grid models that enable variable resolution are ideal for this type of applications, even factoring in the added computational cost due to cache loss (as the memory access is more random than that in structured-grid models). Therefore, in this paper, we will further develop an unstructured grid model for vegetation effects; *the main goal is to develop a 3D model that is efficient enough to simulate the vegetation effects in 3D during long-term evolution of vegetation and over large spatial extents*. A pragmatic definition of efficiency is adopted here; the model is deemed “efficient” if it is possible to conduct multi-year simulations on a realistic bay/estuary system, so as to cover the evolution of vegetation lifecycles. The large spatial extents are necessary to capture

remote influences such as storm surges. *We achieve this goal by embedding all vegetation parameterizations into an implicit solution procedure, so as to not limit the time step*. The hope here is to highlight the importance of proper treatment of the vegetation terms in the 3D model for realistic applications, much like the implicit treatment of equation terms to bypass the CFL restriction (Casulli and Cattani 1994). We demonstrate this new numerical technology using existing physical formulations developed by others (ST94; Lopez and García 2001; Fischer-Antze et al. 2001; Lowe et al. 2005; Li and Yan 2007).

The 3D unstructured grid model, SCHISM (Semi-Implicit Cross-scale Hydrosceince Integrated System Model, Zhang et al. 2016), is an open-source model that is catered to modeling the natural systems where vegetation is commonly found because of the flexible gridding system and the combination of finite-element framework and implicit scheme used in SCHISM. While SCHISM and its predecessors have been applied in a wide range of applications (Burla et al. 2010; Brovchenko et al. 2011; Zhang et al. 2011; Bertin et al. 2012; Rodrigues et al. 2009; Pinto et al. 2012; Roland et al. 2012; Azevedo et al. 2014), vegetation was handled by increasing the bottom roughness parameter (Ye et al. 2013). While the implicit framework used in SCHISM is well positioned for efficiently simulating the vegetation effects over the lifecycles of vegetation, our experience indicated that the additional form drag terms, when treated explicitly, introduced stringent stability constraints on allowable time steps and thus considerably degraded the model efficiency. Such challenges have been similarly reported by Beudin et al. (2017a), who noticed that their split-explicit model “required a reduced time step with the vegetation module (e.g., 1 s instead of 10 s) to eliminate instabilities resulting from sharp velocity gradients”; in other words, the computational time increases by about one order of magnitude with the vegetation included, which is similar to our own experience of treating the drag terms explicitly in our model. The combination of degradation of efficiency and requirement of high resolution locally makes it impossible to conduct long-term, system-wide simulations of vegetation using traditional (structured- or unstructured grid) models. Therefore, our new treatment is critical for field applications that cover large spatial extents and long-term evolution of vegetation, as we will demonstrate in the field study case. With the new treatment, the overhead introduced by the inclusion of vegetation is reduced to only ~15%, and the implicit scheme in SCHISM makes it easy to apply local high resolution in 3D near the vegetation bed. In fact, this new model has been successfully applied to ecosystem studies of real estuaries including the lifecycles of vegetation growth and decay (Cai 2018). The wave attenuation effects following Mendez and Losada (2004) have also been successfully incorporated in the same model but we will focus on flows alone in this paper. For simplicity, we also neglect the differences

between different vegetation species and their interactions (Soliveres and Maestre 2014) but treat them using bulk averaged parameterization.

In this paper, we incorporate the effects of vegetation on currents and turbulence into SCHISM by overhauling the barotropic core of the model. We first briefly review the relevant physical formulations in Section 2. The influence of vegetation is then formulated implicitly to maintain model stability at large time steps (Section 3). The model is validated in Section 4 against lab studies and applied to a field study in San Francisco Bay & Delta area in Section 5 to show the impact of vegetation on seasonal tidal flows. The field estimates of vegetation are derived from remote sensing and GIS product called Normalized Difference Vegetation Index (NDVI; Gandhi et al. 2015). A brief conclusion is drawn in Section 6.

2 Physical formulation

Vegetation is typically modeled as an internal source of resistant force and turbulence energy (ST94; Su and Li 2002; Lopez and García 2001). After the Reynolds averaging procedure in a Cartesian frame (Fig. 1), the Navier-Stokes equations are modified by the addition of a form drag term due to vegetation:

$$\frac{D\mathbf{u}}{dt} = \mathbf{f} - g\nabla\eta + \mathbf{m}_z - \alpha|\mathbf{u}|\mathbf{u}L(x, y, z) \quad (1)$$

Here and below, we use bold letters to denote vectors, and separate out terms that will be treated implicitly. In Eq. (1), $\mathbf{u}$ is the horizontal velocity, D/Dt is the material derivative, $\mathbf{f}$ represents a number of explicitly treated terms (Coriolis, baroclinic pressure gradient, horizontal viscosity etc.; this term should not be confused with the Coriolis term), g is

gravitational acceleration, η is the surface elevation, $\alpha(x, y) = D_v N_v C_{Dv}/2$ is a vegetation-related density variable in m^{-1} , where D_v is the stem diameter, N_v is the vegetation density (number of stems per m^2), and C_{Dv} is the bulk form drag coefficient. Selection of C_{Dv} is the topic of other studies with values varying from very small to 3 (Nepf and Vivoni 2000; Tanino and Nepf 2008), and is validated against reported lab study values; in this paper, we simply adopt the values recommended by other studies. The underlying assumption used here is to treat the vegetation as arrays of solid cylinders, which is only a first-order approximation of the problem. Flexibility of the vegetation, sheltering effects within a cluster of vegetation can lead to one to two orders of reduction in the drag forces, and Gaylord et al. (2008) showed that the drag formulation is also species-dependent. These additional complexities are outside the scope of the current study. In this paper, we assume C_{Dv} is a constant, but a vertically varying C_{Dv} (as suggested by Nepf and Vivoni 2000 and others) can be easily added as well; the latter can be used to approximate flexible stems (Nepf and Vivoni 2000; Luhar and Nepf 2011).

Since SCHISM allows “polymorphism” with mixed 2D and 3D cells in a single grid (Zhang et al. 2016), we have different forms for the vertical eddy viscosity term

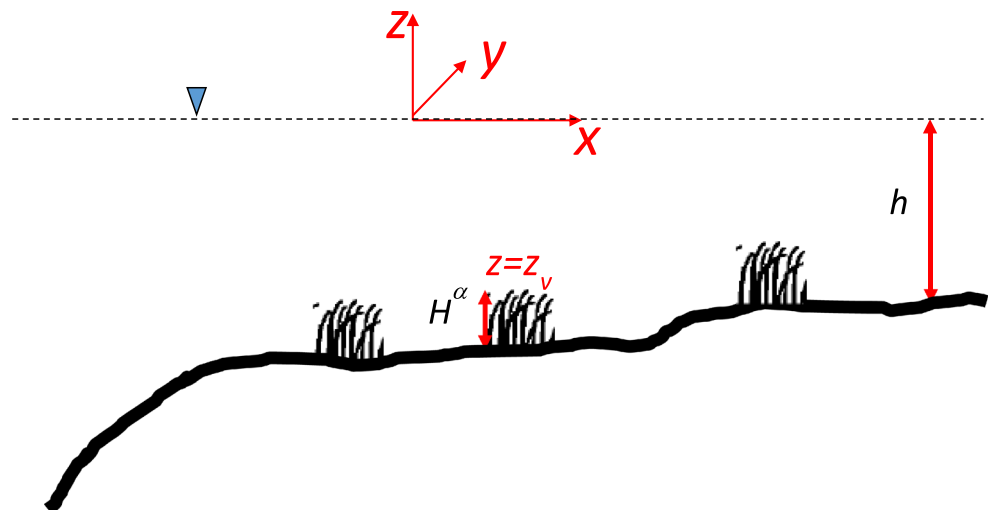
$$m_z = \begin{cases} \frac{\partial}{\partial z} \left(\nu \frac{\partial \mathbf{u}}{\partial z} \right), & \text{3D cells} \\ \frac{\tau_w - \chi \mathbf{u}}{H}, & \text{2D cells} \end{cases} \quad (2)$$

and the vegetation term:

$$L(x, y, z) = \begin{cases} \mathcal{H}(z_v - z), & \text{3D} \\ 1, & \text{2D} \end{cases} \quad (3)$$

where ν is the eddy viscosity, τ_w is the surface wind stress, $H = h + \eta$ is the total water depth (with h being the bathymetry measured from a fixed datum), $\chi = C_D |\mathbf{u}|$, C_D is the bottom

Fig. 1 Domain sketch and coordinate system



drag coefficient, $\mathcal{H}()$ is the Heaviside step function

$$\mathcal{H}(x) = \begin{cases} 1, & x \geq 0 \\ 0, & x < 0 \end{cases} \quad (4)$$

and z_v is the z -coordinate of the canopy. Note that $\mathbf{u}$ denotes the depth-averaged velocity in a 2D region.

For the 3D case, the vertical boundary condition (B.C.) for the Reynolds stress is required to close the system of equations:

$$\begin{cases} \nu \frac{\partial \mathbf{u}}{\partial z} = \boldsymbol{\tau}_w, & z = \eta \\ \nu \frac{\partial \mathbf{u}}{\partial z} = \chi \mathbf{u}_b, & z = -h \end{cases} \quad (5)$$

where $\mathbf{u}_b$ is the near-bottom velocity (evaluated at the top of the bottom cell, which needs to be located inside the bottom-boundary layer). The smooth transition between 2D and 3D cells is ensured as long as there are no sudden jumps in the bottom drag coefficient (Zhang et al. 2016).

The depth-integrated continuity equation is the same as before:

$$\frac{\partial \eta}{\partial t} + \nabla \cdot \int_{-h}^{\eta} \mathbf{u} dz = 0 \quad (6)$$

The vegetation induced turbulence is modeled as an additional source for turbulent kinetic energy (TKE) and mixing length as (ST94):

$$\begin{aligned} \frac{Dk}{Dt} &= \frac{\partial}{\partial z} \left(\nu_k^\psi \frac{\partial k}{\partial z} \right) + \nu M^2 + \kappa N^2 - \epsilon + c_{fk} \alpha |\mathbf{u}|^3 \mathcal{H}(z_v - z) \quad (7) \\ \frac{D\psi}{Dt} &= \frac{\partial}{\partial z} \left(\nu_\psi \frac{\partial \psi}{\partial z} \right) \\ &+ \frac{\psi}{k} \left[c_{\psi 1} \nu M^2 + c_{\psi 3} \kappa N^2 - c_{\psi 2} \epsilon F_{wall} + c_{f\psi} \alpha |\mathbf{u}|^3 \mathcal{H}(z_v - z) \right] \end{aligned} \quad (8)$$

where k is the TKE, ψ is a generic length-scale variable (Umlauf and Burchard 2003), $c_{\psi*}$ are model-specific constants, F_{wall} is a wall proximity function, and νM^2 and κN^2 are shear and buoyancy production terms, respectively. Following ST94, we use the k - ϵ configuration with $c_{fk} = 0.07$ and $c_{f\psi} = 0.16$ in this paper.

3 Numerical model

The new model is built on SCHISM (www.schism.wiki; Zhang et al. 2016), which is a derivative product of SELFIE v3.1dc (Zhang and Baptista 2008), but freely distributed using the Apache v2 license. SCHISM is an open-source community-supported modeling system, based on mixed *triangular-quadrangular* unstructured grids in the horizontal and a very

flexible coordinate system in the vertical (LSC²: Localized Sigma Coordinates with Shaved Cells; Zhang et al. 2015), designed for the effective simulation of 3D baroclinic circulation across creek-to-ocean scales (Zhang et al. 2016). It employs a semi-implicit finite-element/finite-volume method together with an Eulerian-Lagrangian method (ELM) to solve the Navier-Stokes equations in hydrostatic form. As a result, numerical stability is greatly enhanced. The implicit scheme used in SCHISM allows the use of “hyper resolution” (on the order of a few meters) with little penalty on the time step.

Since vegetation is usually present in shallow water with potentially strong velocity shear (cf. Fig. 11), we need to treat the related terms in Eq. (1) implicitly; as a matter of fact, our earlier attempts to treat these terms explicitly (which is much more straightforward to implement) indicated that stability is often compromised. The goal here is to make the numerical stability independent of the vegetation terms, so large time steps (100–300 s for field-scale applications) can be used as before and the whole lifecycle of the vegetation can be effectively simulated. For brevity, we will generally drop superscripts “ n ” (i.e., at step n) associated with the explicit terms in the following derivation and focus on the implicit terms (with superscript “ $n+1$ ”). Table 1 shows the explanations of all symbols used in this paper.

The numerical model starts from a weak form of the Galerkin Finite Element (GFE) formulation for the continuity Eq. (6):

$$\begin{aligned} \int_{\Omega} \phi_i \frac{\eta^{n+1} - \eta^n}{\Delta t} d\Omega + \theta \left[-\int_{\Omega} \nabla \phi_i \cdot \mathbf{U}^{n+1} d\Omega + \int_{\Gamma} \phi_i U_n^{n+1} d\Gamma \right] \\ + (1-\theta) \left[-\int_{\Omega} \nabla \phi_i \cdot \mathbf{U}^n d\Omega + \int_{\Gamma} \phi_i U_n^n d\Gamma \right] \\ = 0, \quad (i = 1, \dots, N_p) \end{aligned} \quad (9)$$

where Ω is the horizontal domain with its boundary Γ , Δt is the time step, ϕ_i is the shape/weighting function with i being a grid node, N_p is the total number of nodes in the horizontal grid, θ is the implicitness factor (e.g., $\theta = 0.5$ leads to the second-order Crank-Nicolson scheme), and $\mathbf{U}$ is the depth-integrated velocity:

$$\mathbf{U} = \int_{-h}^{\eta} \mathbf{u} dz \quad (10)$$

with U_n being its normal component. In this paper, we usually use capital letters to denote depth-integrated quantities. Note that the second integral in the second term in Eq. (9) needs not be evaluated at all; this is because the boundary Γ can be divided into two portions (Neumann and Dirichlet); at the Neumann boundary portion (e.g., river discharge), this term is known. At the Dirichlet boundary portion, the entire Eq. (9) needs not be solved because the elevations there are prescribed. Therefore, the only unknown terms in Eq. (9) are η^{n+1} and $\mathbf{U}^{n+1}$.

Table 1 Symbols used in this paper

Symbol	Explanation	Equation
x, y, z	Cartesian coordinates	1
t	Time	1
$\mathbf{f}$	Explicit terms of momentum equation	1
g	Gravitational acceleration	1
$\mathbf{g}$	Explicit terms of momentum equation	42
$\mathbf{u}$	Horizontal velocity	1
$\mathbf{G}_1$	Explicit terms	21
$\mathbf{G}_2$	Explicit terms	36
$\mathbf{G}_3$	Explicit terms	31
$\mathbf{G}$	Explicit terms	13
h	Bathymetry	2
H	Total water depth	2
$\tilde{H}$	Friction modified depth	23
$\tilde{H}$	Friction modified depth	14
$\underline{H}$	Friction modified depth	34
$\bar{H}$	Friction modified depth	38
H^α	Height of canopy	17
z_v	z -coordinate of canopy	17
E	Explicit terms	39
c	Coefficient	35
U, U_n	Depth-integrated velocity and its normal component	10
U^α	Integrated velocity up to canopy	16
m_z	Vertical viscosity term	2
$L(x,y,z)$	Vertical function of vegetation	3
D_v	Vegetation diameter	1
N_v	Vegetation density	1
C_{D^v}	Form drag coefficient	1
$\mathbf{f}_b, \mathbf{u}_b$	Near-bottom values	18
k	Turbulence kinetic energy	7
$c_{fb}, c_{\psi}[1-3]$	Constants in turbulence closure	8
M^2	Shear frequency	7
N^2	Buoyancy frequency	7
F_{wall}	Wall proximity function	8
$\mathbf{u}^*$	Backtracked velocity	11
N_p	Number of nodes in the grid	9
R_0	Reference stress	26
I	Energy gradient	28
α	Vegetation term	3
β, β_2	Constants used in ST94 theory	27
ν	Viscosity	2
ν_ψ, ν_k^ψ	Turbulence diffusivities	7,8
ε	Turbulence dissipation rate	7
θ	Implicitness factor	9
χ	Related to bottom friction	2
τ_w	Wind stress	2
η	Surface elevation	1
ϕ_i	Horizontal shape function	9
φ_l	Vertical shape function	42
Ω	Horizontal domain	9
Γ	Horizontal boundary	9

The unknown $\mathbf{U}^{n+1}$ is found with the aid from the momentum equation, discretized in time first:

$$\frac{\mathbf{u}^{n+1} - \mathbf{u}^*}{\Delta t} = \mathbf{f} - g\theta \nabla \eta^{n+1} - g(1-\theta) \nabla \eta^n + \mathbf{m}_z^{n+1} - \alpha |\mathbf{u}| \mathbf{u}^{n+1} L(x, y, z) \quad (11)$$

where $\mathbf{u}^*$ is the backtracked value using the Eulerian-Lagrangian method (Zhang and Baptista 2008). Integrating Eq. (11) along the vertical dimension results

in an equation for $\mathbf{U}^{n+1}$, and we discuss three scenarios below.

3.1 Locally 2D case

Since there is only one degree of freedom in the vertical dimension in this case, a straightforward integration of Eq. (11) gives:

$$\mathbf{U}^{n+1} = \mathbf{G} - g\theta \Delta t \frac{H^2}{\tilde{H}} \nabla \eta^{n+1} \quad (12)$$

where $\tilde{\mathbf{G}}$ incorporates explicit terms:

$$\tilde{\mathbf{G}} = \frac{H}{\tilde{H}} [\mathbf{U}^* + \Delta t (\mathbf{F} + \tau_w - g(1-\theta)H\nabla\eta^n)] \quad (13)$$

and $\mathbf{F}$ is the depth-integrated term of $\mathbf{f}$, and $\tilde{H}$ is the depth enhanced by the bottom friction and form drag:

$$\tilde{H} = H + (\chi + \alpha|\mathbf{u}|H)\Delta t \quad (14)$$

The net effect of the vegetation is therefore equivalent to increases in the bottom drag, since the 3D structure of the flow/vegetation is not accounted for. Substituting Eq. (12) into (9) results in an integral equation for the unknown η^{n+1} alone.

3.2 Locally 3D case

We first integrate Eq. (11) from bottom to surface:

$$\frac{U^{(n+1)} - U^*}{\Delta t} = F - gH\theta\nabla\eta^{n+1} - gH(1-\theta)\nabla\eta^n + \tau_w - \chi u_b^{n+1} - \alpha|\mathbf{u}|U^\alpha \quad (15)$$

where we have performed linearization of the vegetation term:

$$\int_{-h}^{z_v} |\mathbf{u}| u dz \approx |\mathbf{u}| \int_{-h}^{z_v} u dz \equiv |\mathbf{u}| U^\alpha \quad (U^\alpha = \int_{-h}^{z_v} u dz) \quad (16)$$

$$|\mathbf{u}| = \frac{1}{H^\alpha} \int_{-h}^{z_v} |\mathbf{u}''| dz \quad (17)$$

and $H^\alpha = z_v + h$ is the height of vegetation. Note that similar procedures have been used for other nonlinear terms (e.g., the quadratic bottom drag).

To eliminate $\mathbf{u}_b^{n+1}$ in Eq. (15), we invoke the discretized momentum equation at the bottom cell and utilize the fact that the Reynolds stress is constant within the boundary layer, as shown in Zhang and Baptista (2008):

$$\frac{\mathbf{u}_b^{n+1} - \mathbf{u}_b^*}{\Delta t} = \mathbf{f}_b - g\theta\nabla\eta^{n+1} - g(1-\theta)\nabla\eta^n - \alpha|\mathbf{u}_b|\mathbf{u}_b^{n+1} \quad (18)$$

from which $\mathbf{u}_b^{n+1}$ can be formally solved as:

$$\mathbf{u}_b^{n+1} = \frac{1}{1 + \alpha|\mathbf{u}_b|\Delta t} [\mathbf{u}_b^* + \mathbf{f}_b\Delta t - g(1-\theta)\Delta t\nabla\eta^n] - \frac{g\theta\Delta t}{1 + \alpha|\mathbf{u}_b|\Delta t} \nabla\eta^{n+1} \quad (19)$$

The subscript “b” denotes the top of the bottom cell. Note that the main difference from the original formulation of Zhang and Baptista (2008) is the appearance of the vegetation term.

The remaining task is to find $\mathbf{U}^\alpha$. We will discuss two scenarios of submerged and emergent vegetation.

3.2.1 Emergent vegetation

When the vegetation is *locally* emergent, i.e., $H^\alpha \geq H$, we have $\mathbf{U}^\alpha = \mathbf{U}^{n+1}$, and therefore, $\mathbf{U}^{n+1}$ can be found from Eqs. (15) and (19) as:

$$\mathbf{U}^{n+1} = \mathbf{G}_1 - \frac{g\theta\hat{H}\Delta t}{1 + \alpha|\mathbf{u}|\Delta t} \nabla\eta^{n+1} \quad (20)$$

where $\mathbf{G}_1$ contains explicit terms:

$$\mathbf{G}_1 = \frac{\mathbf{U}^* + (\mathbf{F} + \tau_w)\Delta t - g(1-\theta)\hat{H}\Delta t\nabla\eta^n - \tilde{\chi}\Delta t(\mathbf{u}_b^* + \mathbf{f}_b\Delta t)}{1 + \alpha|\mathbf{u}|\Delta t} \quad (21)$$

$$\tilde{\chi} = \frac{\chi}{1 + \alpha|\mathbf{u}_b|\Delta t} \quad (22)$$

and $\hat{H}$ is a friction modified depth:

$$\hat{H} = H - \tilde{\chi}\Delta t \quad (23)$$

Compared with the original formulation in Zhang and Baptista (2008), the only change in this depth is the vegetation term in $\tilde{\chi}$.

3.2.2 Submerged vegetation

When the vegetation is submerged, i.e., $H^\alpha < H$, strong shear and turbulence develop between the vegetation and the overlying flow above it (ST94). Nepf and Vivoni (2000) demonstrated that there are two zones for submerged aquatic vegetation (SAV). In the upper canopy (called the “vertical exchange zone”), mean shear at the top of the canopy produces vertical turbulent exchange with the overlying water, which plays a significant role in the momentum balance. The lower canopy (“longitudinal change zone” as in Nepf and Vivoni 2000) communicates with surrounding water predominantly through longitudinal advection. The extent of the vertical exchange of momentum between the vegetation zone and overlying water is dependent on the submergence.

We first integrate the momentum Eq. (11) from the bottom to the top of canopy:

$$\begin{aligned} \mathbf{U}^\alpha &= \mathbf{U}^{*\alpha} \\ &+ \mathbf{F}^\alpha\Delta t - g\theta H^\alpha\Delta t\nabla\eta^{n+1} - g(1-\theta)H^\alpha\Delta t\nabla\eta^n - \alpha\Delta t|\mathbf{u}|\mathbf{U}^\alpha \\ &+ \Delta t\nu \frac{\partial \mathbf{u}}{\partial z} \Big|_{-h}^{z_v} \end{aligned} \quad (24)$$

where

$$U^{*\alpha} = \int_{-h}^{z_v} \mathbf{u}^* dz, \quad \mathbf{F}^\alpha = \int_{-h}^{z_v} \mathbf{f} dz \quad (25)$$

The Reynolds stress at the top of canopy can be calculated from theory proposed by ST94. These authors found through lab experiments that the stress variation inside the vegetation layer approximately follows an exponential law:

$$\nu \frac{\partial \mathbf{u}}{\partial z} \equiv \mathbf{u}' w' = \mathbf{R}_0 e^{\beta_2(z-z_v)}, \quad (z \leq z_v) \quad (26)$$

where $\mathbf{R}_0$ is the stress at $z = z_v$, and β_2 is determined by an empirical formula:

$$\beta_2 = \sqrt{\frac{\sqrt{N_v}}{H^\alpha}} \left[-0.32 - 0.85 \log_{10} \left(\frac{H - H^\alpha}{H^\alpha} I \right) \right] \quad (27)$$

where I is an energy gradient:

$$I = \frac{\chi |\mathbf{u}_b|}{gH} \quad (28)$$

which is estimated from the previous time step in the model.

The stress term in Eq. (24) therefore becomes:

$$\nu \frac{\partial \mathbf{u}}{\partial z} \Big|_{-h}^{z_v} = \beta \chi \mathbf{u}_b^{n+1} \quad (29)$$

where $\beta = e^{\beta_2(z_v - z_b)} - 1$, and z_b is the location of the top of the bottom grid cell. Substituting Eqs. (29) and (19) into (24), we can “solve” for $\mathbf{U}^\alpha$ as:

$$\mathbf{U}^\alpha = \mathbf{G}_3 - \frac{g\theta \hat{H}^\alpha \Delta t}{1 + \alpha |\mathbf{u}| \Delta t} \nabla \eta^{n+1} \quad (30)$$

$$\mathbf{G}_3 = \frac{\mathbf{U}^{*\alpha} + \mathbf{F}^\alpha \Delta t + \beta \tilde{\chi} \Delta t (\mathbf{u}_b^* + \mathbf{f}_b \Delta t) - g(1-\theta) \hat{H}^\alpha \Delta t \nabla \eta^n}{1 + \alpha |\mathbf{u}| \Delta t} \quad (31)$$

$$\hat{H}^\alpha = H^\alpha + \beta \tilde{\chi} \Delta t \quad (32)$$

Finally, substituting Eqs. (30) and (19) into (15) results in a relationship between $\mathbf{U}^{n+1}$ and η^{n+1} :

$$\mathbf{U}^{(n+1)} = G_2 - g\theta \bar{\bar{H}} \Delta t \nabla \eta^{(n+1)} \quad (33)$$

$$\bar{\bar{H}} = H - \tilde{X} \Delta t - c \hat{H}^\alpha \quad (34)$$

$$c = \frac{\alpha |\mathbf{u}| \Delta t}{1 + \alpha |\mathbf{u}| \Delta t} \quad (35)$$

$$G_2 = \mathbf{U}^* - c \mathbf{U}^{(*)} + (F + \tau_v) \Delta t - c F^\alpha \Delta t - \tilde{X} \Delta t (1 + \beta c) (\mathbf{u}_b^* + \mathbf{f}_b \Delta t) - g(1-\theta) \bar{\bar{H}} \Delta t \nabla \eta^n \quad (36)$$

3.3 General case

In summary, the depth-integrated velocity can be expressed in compact form as:

$$\mathbf{U}^{(n+1)} = E - g\theta \bar{\bar{H}} \Delta t \nabla \eta^{(n+1)} \quad (37)$$

where

$$\bar{\bar{H}} = \begin{cases} \frac{H^2}{\hat{H}}, & 2D \\ \frac{\hat{H}}{1 + \frac{\alpha |\mathbf{u}| \Delta t}{\hat{H}}}, & 3D \text{ emergent} \\ \bar{H}, & 3D \text{ submerged} \end{cases} \quad (38)$$

$$E = \begin{cases} \bar{G}, & 2D \\ G_1, & 3D \text{ emergent} \\ G_2, & 3D \text{ submerged} \end{cases} \quad (39)$$

Substituting Eq. (37) back into (9) gives an equation for the unknown elevations alone:

$$\begin{aligned} \int_{\Omega} [\phi_i \eta^{(n+1)} + g\theta^2 \Delta t^2 \bar{\bar{H}} \Delta \phi_i \cdot \nabla \eta^{(n+1)}] d\Omega \\ = \int_{\Omega} [\phi_i \eta^n + \Delta t \nabla \phi_i \cdot E + (1-\theta) \Delta t \nabla \phi_i \cdot \mathbf{U}^n] d\Omega - \theta \Delta t \int_{\Gamma} \phi_{ii} U_n^{(n+1)} d\Gamma \\ - (1-\theta) \Delta t \int_{\Gamma} \phi_i U_n^n d\Gamma = 0 \quad (i = 1, \dots, N_p) \end{aligned} \quad (40)$$

Note that the boundary integral term involving U_n^{n+1} is known at the Neumann-type boundary segments. The matrix associated with Eq. (40) is symmetric and positive definite, as long as the depth $\bar{\bar{H}}$ is non-negative (Zhang and Baptista 2008). The effects of the vegetation on $\bar{\bar{H}}$ are generally similar to the bottom friction. For the 2D case, $\bar{\bar{H}}$ is always positive. For the 3D emergent case, the vegetation term in the denominator in Eq. (38) is positive and so $\bar{\bar{H}}$ is usually positive as $\hat{H}$ is usually positive (Zhang and Baptista 2008). For the 3D submerged case, as $\alpha \rightarrow 0$, previous results of Zhang and Baptista (2008) are recovered. As $\alpha \rightarrow \infty$ (i.e. very dense vegetation), the friction term (the second term in Eq. (34)) dwarfs in comparison with the vegetation term (the third term in Eq. (34)), and therefore, the bottom friction is negligible under dense vegetation. Since $c \rightarrow 1$ as $\alpha \rightarrow \infty$, $\bar{\bar{H}}$ approaches the submergence, $H - H^\alpha$ which is positive by definition. When the submergence is very small (i.e., almost emergent vegetation), $\bar{\bar{H}} \rightarrow 0$ and the conditioning of the matrix would somewhat deteriorate but the model remains stable. Physically, this means that very strong shear will develop near the canopy (e.g., Fig. 11).

3.4 Momentum equation

After the unknown elevations are solved at all nodes, the momentum equation is solved along the vertical column of each side using a GFE method. We again discuss the cases of 2D and 3D separately.

3.4.1 2D case

Equation (11) can be directly solved for the unknown depth-averaged velocity:

$$\mathbf{u}^{(n+1)} = \frac{\bar{H}}{H} [\mathbf{u}^* + (f + \tau_w/H) \Delta t - g \theta \nabla \eta^{n+1} - g(1-\theta) \nabla \eta^n] \quad (41)$$

3.4.2 D case

The 3D equation is solved at a side from $z = z_b$ to η using a GFE method:

$$\int_{z_b}^{\eta} \varphi_l \left[b \mathbf{u}^{n+1} - \Delta t \frac{\partial}{\partial z} \left(\nu \frac{\partial \mathbf{u}^{n+1}}{\partial z} \right) \right] dz = \int_{z_b}^{\eta} \varphi_l \mathbf{g} dz, \quad (l = k_b + 1, \dots, N_z) \quad (42)$$

where φ_l is the vertical hat function, k_b is the local bottom index, N_z is the surface index, $b = 1 + \alpha |\mathbf{u}^n| \Delta t \mathcal{H}(z_v - z)$, and $\mathbf{g}$ contains all explicit terms. Equation (42) is then integrated by parts (with the aid of B.C. Equation (5)) and solved as before. The resultant matrix is tri-diagonal and can be solved efficiently. Note that when solving the momentum equation, we committed a small inconsistency by not using the exponential law in Eq. (26), because Eqs. (1) and (5) already form a closed system; this, however, seems to only have a minor impact on the model results (not shown).

3.5 Turbulence closure

The original solver uses a GFE method to solve the k and ψ along the vertical column of each node (Zhang and Baptista 2008). The production term (i.e., the sum of shear and buoyancy) in each equation is treated either explicitly (when it is positive) or implicitly (when it is non-positive) to enhance stability. The additional terms resulting from the vegetation can be easily lumped into the production terms and so the modification is minimal.

4 Model validation

In this section, we will validate the new vegetation model using carefully measured lab data and the results from other

models. We demonstrate that the new model is able to reasonably capture the 3D flow structure around the vegetation.

4.1 Shimizu and Tsujimoto (1994)

These authors studied the flow and turbulence over a vegetation layer in a lab, analyzed the velocity and stress distributions for steady and unsteady flows, and compared the lab data with model predictions. Here, we use two cases (R32 and A71) from the steady flow case to quantitatively validate our new SCHISM. The vegetation parameters used in these two cases are shown in Table 2.

The parameters used in our modeling study are largely taken from Shimizu and Tsujimoto (1994) when appropriate. We use a uniform grid $\Delta x = \Delta y = 0.25$ m to cover the flume domain of $10 \text{ m} \times 2 \text{ m}$. The bottom slope is first adjusted so as to obtain a uniform flow in the domain without the vegetation, as reported in Shimizu and Tsujimoto (1994). The slope is found to be 0.003 for R32 and 0.01 for A71. Similar to ST94, a uniform 21 σ levels is used to resolve the vertical dimension. The form drag coefficient is $C_{Dv} = 1$. The modeled depth-averaged velocity is found to be mostly uniform along the flume with the depth-averaged velocity within 2% of the lab data (Table 2), which confirms that the flow without vegetation has been properly set up. The model is run for 750 s with a time step of 1 s, but a steady state is established after 100 s.

The comparison of velocity profiles is shown in Figs. 2a and 3a for the two cases. The agreement between the model and lab data is quite reasonable in general, with an averaged root-mean-square error (RMSE) of 1.85 cm/s. The velocity inside the vegetation layer is particularly well simulated, and less so for the flow above the canopy. The model captured the strong impedance of the flow by the vegetation layer and strong shear near the canopy. The larger inflow in A71 has led to a larger flow and shear, which has somewhat eroded the low-flow zone inside the vegetated layer (Fig. 3a). On the other hand, without the vegetation, the flow structures resemble a typical open channel flow, with much larger velocity near bed than in the case with vegetation (Figs. 2a and 3a). To examine the sensitivity with respect to C_{Dv} , the results with its value halved and doubled are also shown in Figs. 2a and 3a. Larger C_{Dv} tends to slow down the flow throughout the water column, with greater slowdown below the canopy where the vegetation effects are strongest.

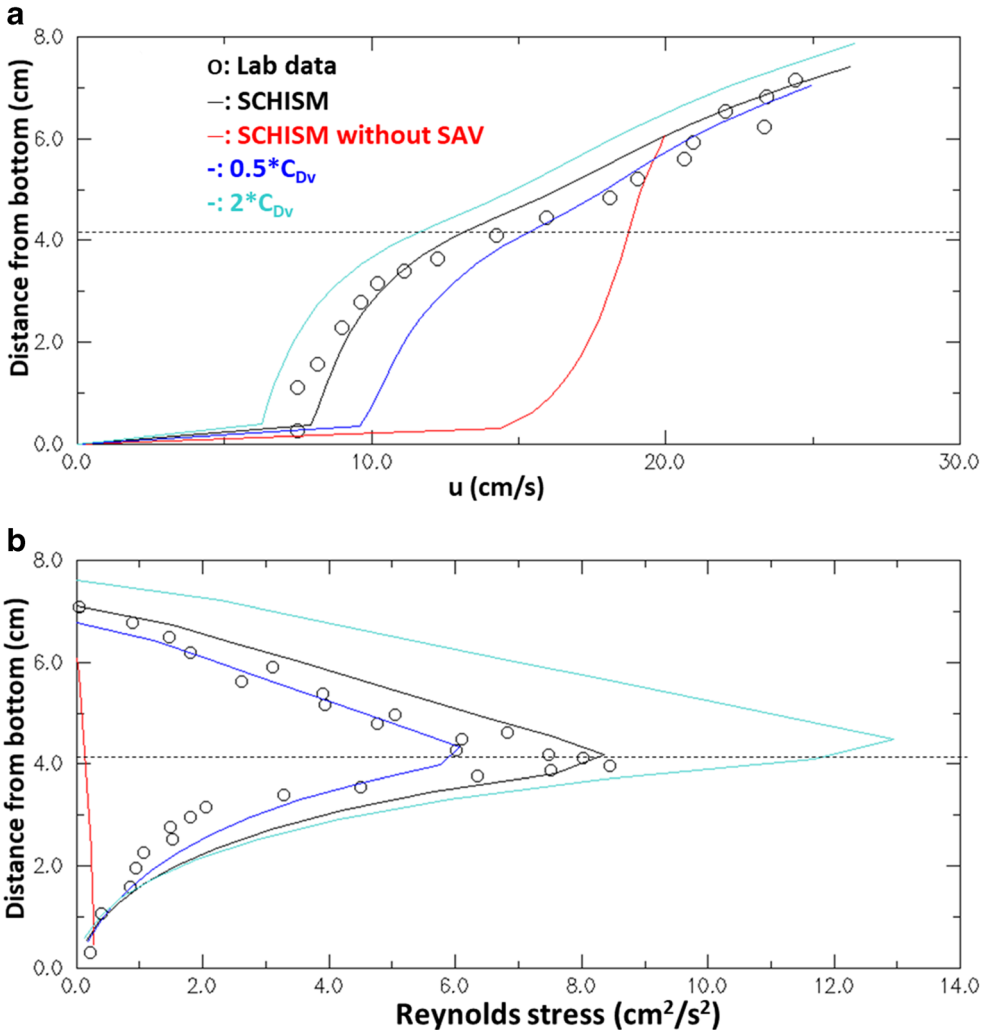
The simulated shear stress ($\nu \partial u / \partial z$) is also compared reasonably with the lab data (for R32; Fig. 2b) and ST94 results (for A71; Fig. 3b). The RMSE for the R32 case is $1.2 \text{ cm}^2/\text{s}^2$. There are errors both inside and outside the vegetation layer, similar to ST94 (Fig. 2b). The magnitude and location of the maximum shear stress are modeled well; both lab and model

Table 2 Parameters used in 2 cases of ST94

	D (cm)	H^a (cm)	N (cm ⁻²)	H (cm)	Depth-averaged velocity from lab (cm/s)	Depth-averaged velocity from model (cm/s)
R32	0.1	4.1	1	7.47	13.87	13.6
A71	0.15	4.6	0.25	8.95	33.05	33.1

results suggest that the strongest shear occurs near the top of the canopy. Our modeled maximum stress for A71 (Fig. 3b) also matches that in the model results of ST94, but its location is a little higher above the canopy. Without the vegetation, the stress is much smaller with a maximum value near the bed (Figs. 2b and 3b). Sensitivity results with respect to C_{Dv} indicate that larger drag leads to larger shear and stress, but the location of the maximum remains above the canopy in all cases. In summary, the new model is able to reasonably capture the complex flow and turbulence structures in this lab test. The structures are qualitatively consistent even under significant parameter variation, particularly compared with a case without vegetation, and this point is important in field applications (Section 5) conducted under more uncertainty.

Fig. 2 Comparison of vertical profiles of **a** velocity; **b** Reynolds stress for case R32 in ST94. The dashed lines represent the height of vegetation. Note that the cases with and without SAV have different surface elevations. The sensitivity results with the drag coefficient halved and doubled are also shown

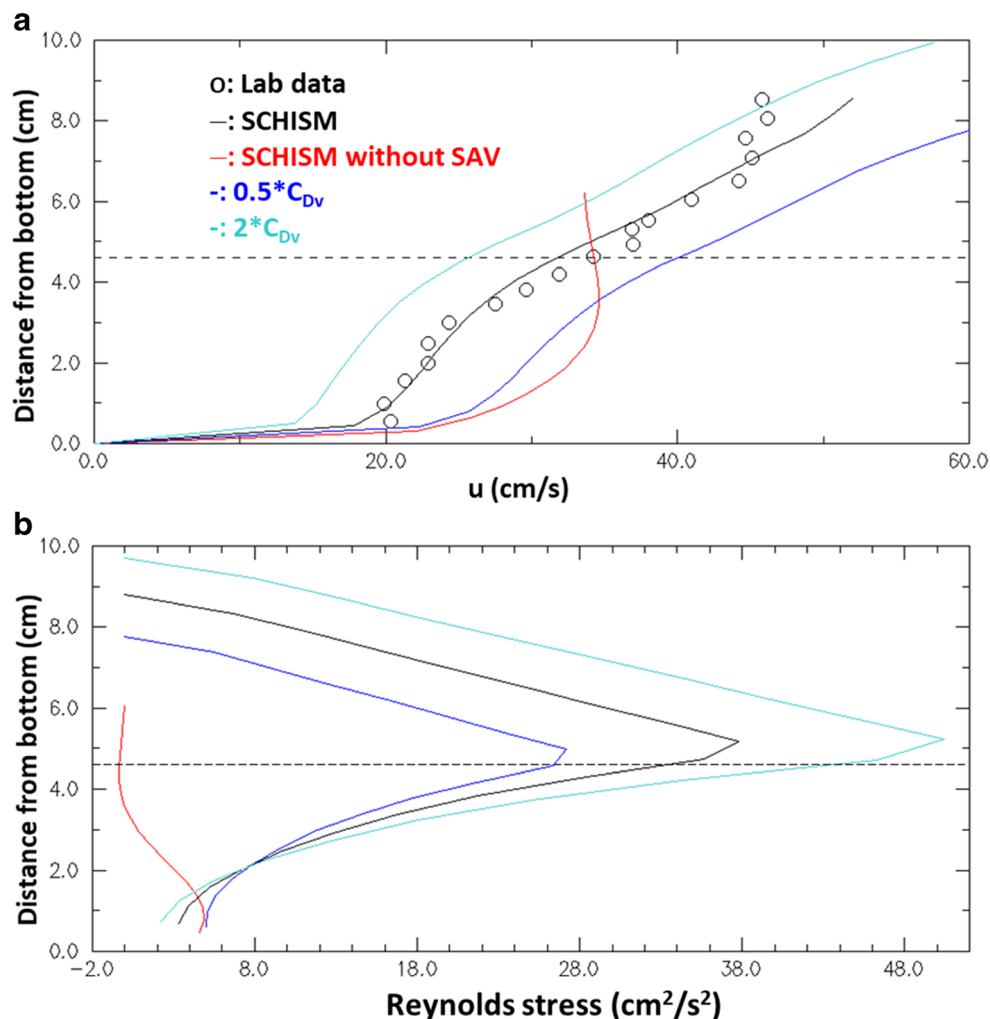


4.2 Su and Li (2002)

These authors (SL02 hereafter) studied flow over a straight flume with emergent vegetation only on one side of the channel (as shown in Fig. 4). The lab experiment was originally conducted by Tsujimoto and Kitamura (1992). SL02 developed an LES model to simulate both the mean flow and evolution of large eddies. Since our model is hydrostatic, here, we only strive to compare our model results for the mean flow.

We use the setup of the 1st case (A1) in SL02, with parameters shown in Table 3. The domain is 60 cm $\times$ 40 cm with a uniform water depth of 4.57 cm. The vegetation layer covers a 12-cm-wide area from one side of the lateral boundary (Fig. 4). The parameters used in our modeling study are largely

Fig. 3 Comparison of vertical profiles of **a** velocity; **b** Reynolds stress for case A71 in ST94. Note that there is no lab data for stress but it can be compared with the model results of ST94. The dashed lines represent the height of vegetation. Note that the cases with and without SAV have different surface elevations. The sensitivity results with the drag coefficient halved and doubled are also shown



consistent with those in SL02. The horizontal resolution is $\Delta x = 1$ cm, $\Delta y = 0.5$ cm, and 11 σ levels (similar to SL02) are used to resolve the vertical structure. The time step used is 0.005 s and the total simulation period is 20 s but a quasi-steady state is established after 10 s. The simulation finishes in 2 s on 32 CPUs of an Intel Xeon cluster. The vegetation-induced drag coefficient is $C_{Dv} = 0.89$ after accounting for a shade factor of 0.448 (SL02), which is consistent with the value suggested by Nepf and Vivoni (2000) for emergent vegetation. The roughness of the bed is 1 cm.

In order to obtain the averaged flow velocity as observed in the lab, we first set up the model without the vegetation. The bottom slope is adjusted to obtain a quasi-uniform flow of ~ 32 cm/s (as reported in the lab experiment), and a final slope value of 0.002 is chosen this way to match the lab observed flow (Table 3). After the initial flow field is properly set up, the model run is then repeated with the vegetation added.

The quasi-steady state surface velocity obtained from the model (not shown) suggests a strong impedance by the vegetated area, with a strong lateral shear present near the boundary of vegetated and non-vegetated areas. The results

qualitatively agree with those in SL02. A quantitative assessment of the lateral distribution of the surface velocity is shown in Fig. 5. Our model results seem to be generally consistent with SL02 (cf. their Fig. 6a) and both models exaggerated the lateral shear in the transition zone. Our model also captured the maximum velocity in the middle of the non-vegetated

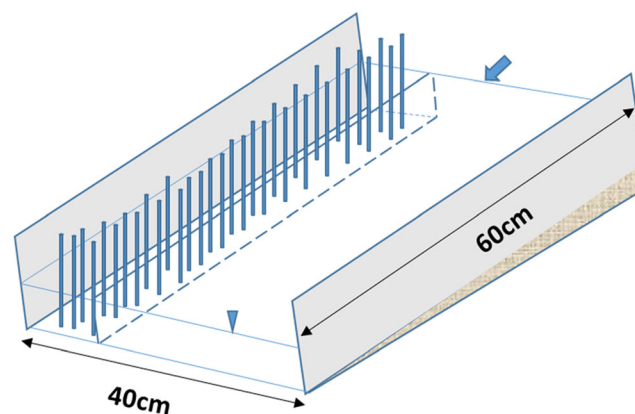


Fig. 4 SL02 case setup. The sticks represent the vegetation and the channel is tilted to generate a uniform flow

Table 3 Model parameters used in SL02

D (cm)	N (cm ⁻²)	H (cm)	Depth-averaged velocity from lab (cm/s)	Depth-averaged velocity from model (cm/s)
0.02	30	4.57	32	32.7

area, although it occurs too close to the vegetated area (i.e., peaked too soon) due to over-estimation of the lateral shear. The RMSE error for this comparison is 4.5 cm/s. Sensitivity results with respect to C_{Dv} , as shown in Fig. 5 suggest that a larger C_{Dv} would slow down the flow inside the vegetated area while increasing the flow outside due to conservation of total volume; a smaller C_{Dv} , on the other hand, would result in better agreement with the lab data (Fig. 5).

These results suggest that the new SCHISM is able to reasonably capture the 3D flow structure around the vegetation and the physical and numerical formulations presented in Sections 2 and 3 are sound.

5 Field application

5.1 System description

Having validated the model for the lab tests, we now apply it to the study of a field case of tidal flow in Franks Tract (Fig. 6), a shallow water body in the San Francisco Bay-Delta whose dynamics are strongly influenced by SAV. We demonstrate for such a realistic system the efficiency of the flow model, which serves as a foundation to the full ecosystem model described in Cai (2018).

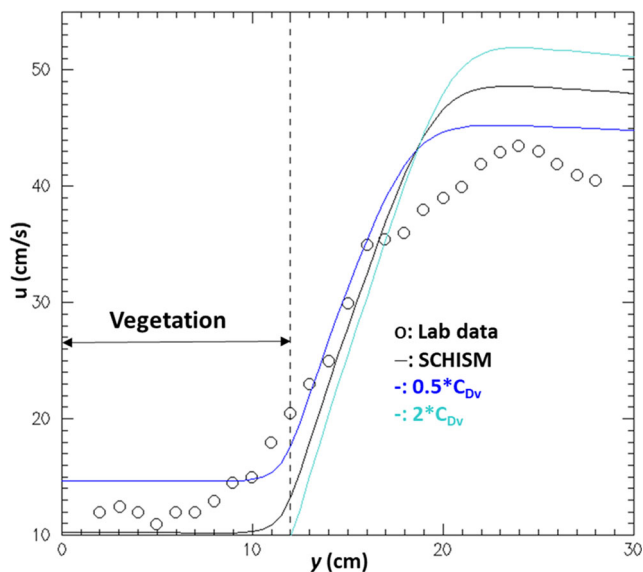


Fig. 5 Comparison of lateral distribution of surface u -velocity. The lab data are from Tsujimoto and Kitamura (1992). The sensitivity results with the drag coefficient halved and doubled are also shown

Franks Tract is a historically flooded island that is of importance because it lies at the transition between the more saline lower estuary and the “freshwater corridor” of the Sacramento-San Joaquin Delta used to convey much of California’s water supply from the Sacramento River to pumps in the south Delta. Franks Tract is just under 1900 ha in area and ~2 m in depth, connected in several places to leveed channels at its perimeter. The largest volume of tidal exchange into Franks Tract is through the False River (Fig. 7), which forms a traditional tidal pump. To the northeast of Franks Tract, a short segment of the Old River connecting the tract to the San Joaquin River forms a second and more complex path for tidal influx (Fig. 7).

Franks Tract is dense with vegetation, and the density changes over time in recent years, affecting both the ecological value and water supply and conveyance of the channel system. Figure 7 is a map of normalized difference vegetation index (NDVI) that has been binned to highlight the presence of SAV. Different species dominate year to year, including native and invasive species of pondweed and *Egeria densa*. A channel can be seen through the SAV that is cleared by the jet from False River (cf. Fig. 7). The corridor through the vegetation has historically been self-reinforcing over an annual cycle and has been structurally similar from year to year at least until 2015 when vegetation colonization appears to have accelerated. Seasonal and decadal trends are important and modulate the whole field: vegetation is densest in the summer growth season and senescent in winter.

The effect of SAV on circulation in Franks Tract has been described previously by Lucas and Stewart (2005), who noted both horizontal shear between open and vegetated areas and vertical shear above the canopy. SAV also affects tidal energetics at a regional and seasonal scale. This is evident in discharge time series at the USGS station Old River at Franks Tract, whose tidal range increases during the vegetation growth season (cf. Fig. 12).

5.2 Model setup

The Franks Tract portion of our mesh (Fig. 8) is embedded within a larger domain encompassing the entire San Francisco Bay-Delta. The Bay-Delta SCHISM is an estuary scale model developed collaboratively by the California Department of Water Resources and Virginia Institute of Marine Science (Ateljevich et al. 2014). The most current version has 183,000 triangular and quadratic elements, and the horizontal resolution over the full domain varies from 5 m in a small

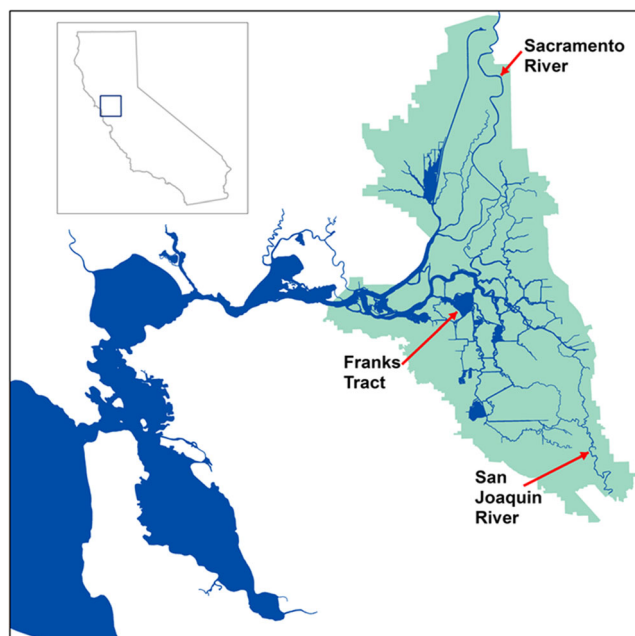


Fig. 6 Location of Franks Tract in the San Francisco Bay-Delta

number of narrow small channels to 2 km on the near coast, but is mostly 10–70 m in Franks Tract with higher resolution concentrated near the inlets. The model employs an adaptive, terrain conforming vertical discretization ranging from 23 vertical layers near the coast to a single (2D) layer at the upstream reaches of the Sacramento and San Joaquin Rivers. Within Franks Tract, there are 16 levels covering the roughly 2 m depth with 6–8 of those levels concentrated above the canopy near mean tide. This is more than the 9 evenly spaced sigma levels typically used to resolve velocity in Franks Tract when vegetation is not considered, the addition coming from the need to resolve the narrow boundary layer between the canopy and surface. Importantly, although the added resolution is controlled by the vegetation, global performance of the model is

impacted only modestly. With a non-split time step of 90 s (for both external and internal modes), the model runs 150 times faster than real time on 128 CPUs of the same Intel cluster. The computational overhead with the addition of SAV is merely ~15%, which is in stark contrast to the explicit models mentioned in the introduction.

The hydrodynamic forcing for our simulations comes from 2009 to 2010 historical conditions and mostly follows the description of boundary conditions in Ateljevich et al. (2014), including upstream inflows from USGS gages, pumping volumes from water project operators and tide data along the near coast. One notable change in our modeling inputs is wind, which is now interpolated from 69 field stations including one at Bethel Island near Franks Tract. The model uses a $k-\omega$ turbulence closure; substitution of other closures (e.g., $k-\epsilon$) does not alter the effect of SAV on velocity structure qualitatively.

For lack of SAV characterization specific to the year 2009, our SAV characterization comes from remote sensing maps from 2004 (Fig. 7). We estimated density using binned NDVI images (Fig. 7) from interpolating stem densities between 20 and 100 stems/m². The method is similar to that of Kimmerer et al. (2019), and rescales raw NDVI to account for numerical ranges (low values and saturation) where the scale does not smoothly represent changes in vegetation. The canopy was set to a uniform canopy elevation at 0.25 m NAVD88 (North American Vertical Datum of 1988), an elevation that is not far from the surface but always submerged, a condition routinely observed in summer. It is pointed out by Cho et al. (2008) that NDVI is less accurate for measuring SAV at depths than it is for floating species. On the other hand, species composition in the years considered was dominated by *Egeria densa*, which has a more consistent density through the canopy than many other local species. This consistency helps to make surface observations more representative of the water

Fig. 7 Close-up of Franks Tract with binned values of normalized vegetation density index (NDVI). Adapted from Hestir et al. (2008) and Khanna et al. (2011)

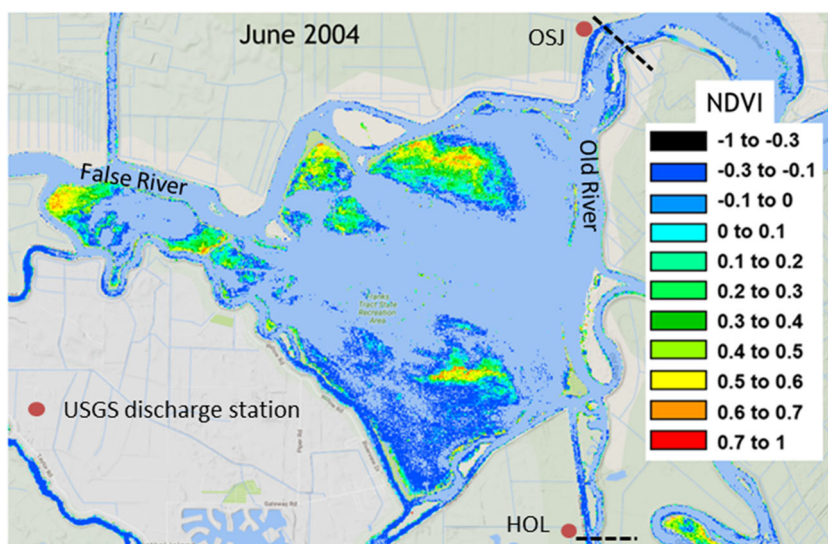
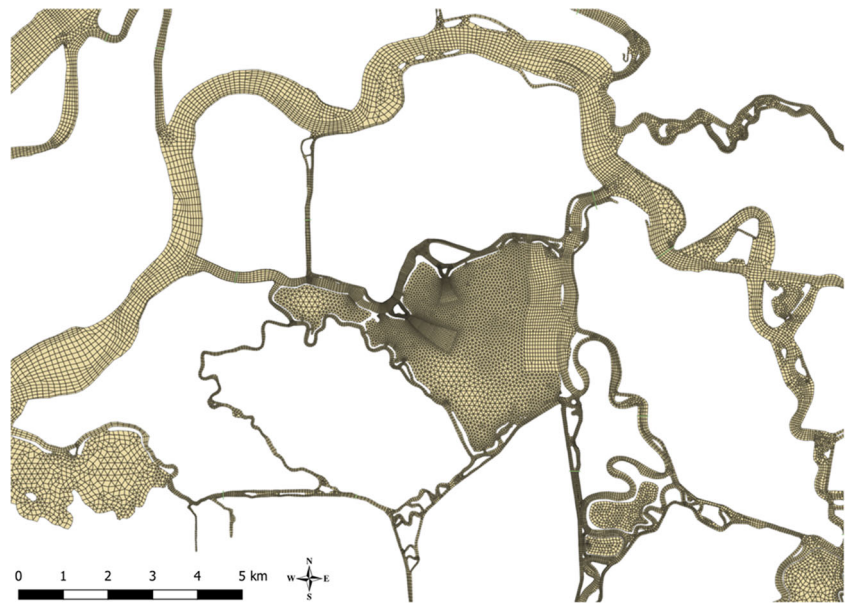


Fig. 8 Franks Tract portion of the full Bay-Delta mesh



column as long as the canopy is not far from surface. In deeper water, the canopy may not reach the surface even at low tide, and this would lead to a measurement bias that exaggerates the biological tendency for denser vegetation in shallow water.

The practical requirements for the model described in this paper include a drag coefficient, canopy height, stem density, and diameter, the latter two being multiplied to give effective drag area per unit volume. There is some debate in the literature over the proper scale to define drag elements (Statzner et al. 2006)—for instance, based on total wetted area of all the leaves, diameter of a single stem or projected frontal area of the plant. Many interpretations of drag area can be shoehorned into our parameterization with a suitable choice of “diameter” and “density.” Ultimately, we based our drag elements on stems which were easier for us to observe. The width of individual stems was set to 3 cm based on rake samples in nearby parts of the estuary. We used a drag coefficient of 1.13. The choices of canopy height and stem density have been explained in the previous paragraph.

5.3 Model results

The local effect of vegetation on horizontal flow patterns is strong. Figure 9 shows the horizontal velocity on flood tide without SAV and with SAV. Without SAV, flood flows in the False River jet are more diffuse. The main jet is wider, contributing to significant velocity over much of the Tract. Circulation occurs in the areas that are not isolated from primary flow. By contrast, in the case with SAV, flow is clearly channelized, tightly corralled on both sides by vegetation. The main current is stronger, but the vegetation allows little circulation away from the main channel. Figure 10 shows flow on an ebb tide without and with vegetation. Without SAV, the

flow takes on a radial pattern reminiscent of tidal pumping; by contrast, with SAV the flow remains channelized on ebb tide.

Figure 11 reveals the vertical profiles of the horizontal velocity magnitude, taken along the transect indicated by the dashed lines in Fig. 9. The plots are taken at flood tide and correspond in time to the depth-averaged velocity in Fig. 9. Note that SAV is absent in the deeper channels and so the canopy appears to be “truncated” there.

In the case without SAV, the boundary layer is confined to the region near the bed, with much of the Tract supporting velocities greater than 10 cm/s. The transition from the jets to open water is also comparatively gradual. By contrast, in the vegetated case velocities develop mostly in the narrow region above the canopy. Velocity above the canopy exceeds 10 cm/s even in some areas away from the main jets; by contrast, velocities a short distance below the canopy rarely reach 2 cm/s. The horizontal and vertical velocity shear is qualitatively similar to that observed by Lucas and Stewart (2005) and represents an important characteristic of local transport. Episodic shear flow over the top of the vegetation has a capacity to redistribute constituents and organisms positioned deeply within the SAV, remote from open water.

Besides changing local velocity, SAV in Franks Tract plays a modest role in regional tidal energetics by attenuating tides from the False River. Figure 12 shows modeled tidal discharge at two USGS discharge stations, Old River at Franks Tract (OSJ in Fig. 7) and Holland Cut (HOL in Fig. 7). Comparing the two simulations, SAV increases tidal range of flow through OSJ and decreases it through HOL. In both cases, the change is due to the dissipation of tides propagating from the False River. The tides exit Franks Tract to the east in such a way that they oppose tides

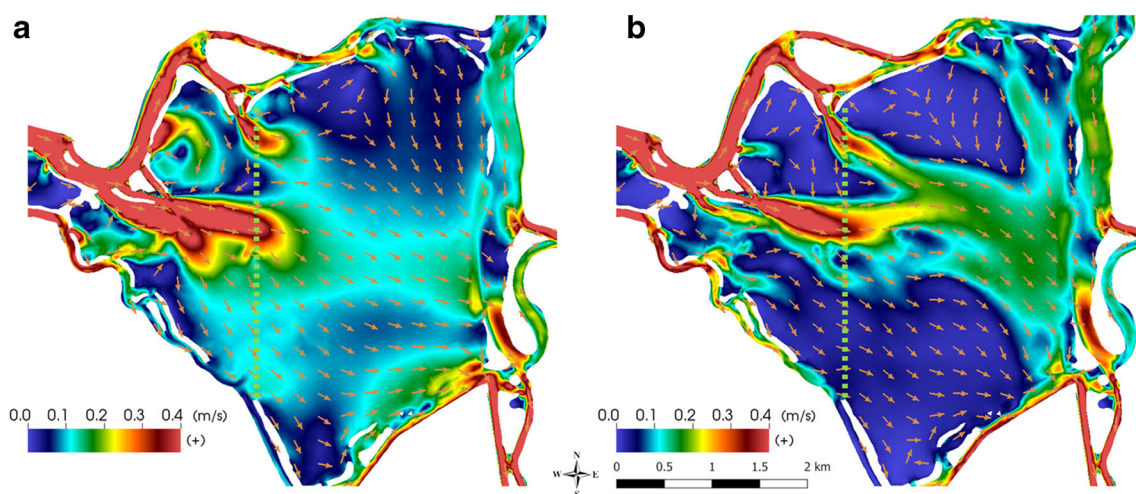


Fig. 9 Depth-averaged velocity patterns (a) without and (b) with SAV on August 2, 2009 at 11:40 during flood tide. Arrows describe direction and colors describe magnitude. The dashed line shows the position of the vertical profile plots in Fig. 11

arriving at OSJ from the San Joaquin and augment them as they propagate south towards HOL. The change in modeled amplitude is approximately 6%. The model result suggests we would see similar differences in field observations between the dense growth season in late summer and the senescent season of late winter. Indeed, based on discharge data from 2008 through 2014, the amplitude of M2 is 5% higher at OSJ and 4% lower at HOL during July and August; the amplitudes of the constituents K1 and O1 are 2% higher at OSJ and 10% lower at HOL during February and March. While some seasonal modulation in the tidal admittance of the estuary is to be expected due to differences in mean flow and wind, the timing of the shift in tidal range does not coincide as well with either of these alternate explanations; additionally, the signature of the change in tidal

range (one station increasing and the other decreasing) is easier to reproduce using vegetation.

The presence of SAV has significant implications for water quality. For example, the water age, calculated from the theory of Deleersnijder et al. (2001), is changed up to a few days (Fig. 13). For this purpose, an age “tracer” is injected from the San Joaquin River boundary, where most of the water in Franks Tract comes from. The changes are largely consistent with the distribution of SAV bed (Fig. 7): the age is increased over the bed and decreased in the deeper channels (Fig. 13c). The largest increase occurs in the southern part of the domain due to a recirculation zone over the SAV bed there (Figs. 9 and 10). The relatively high baseline ages (~50 days) in the plot are due to the fact that Vernalis boundary on the San Joaquin River is approximately 80 km upstream.

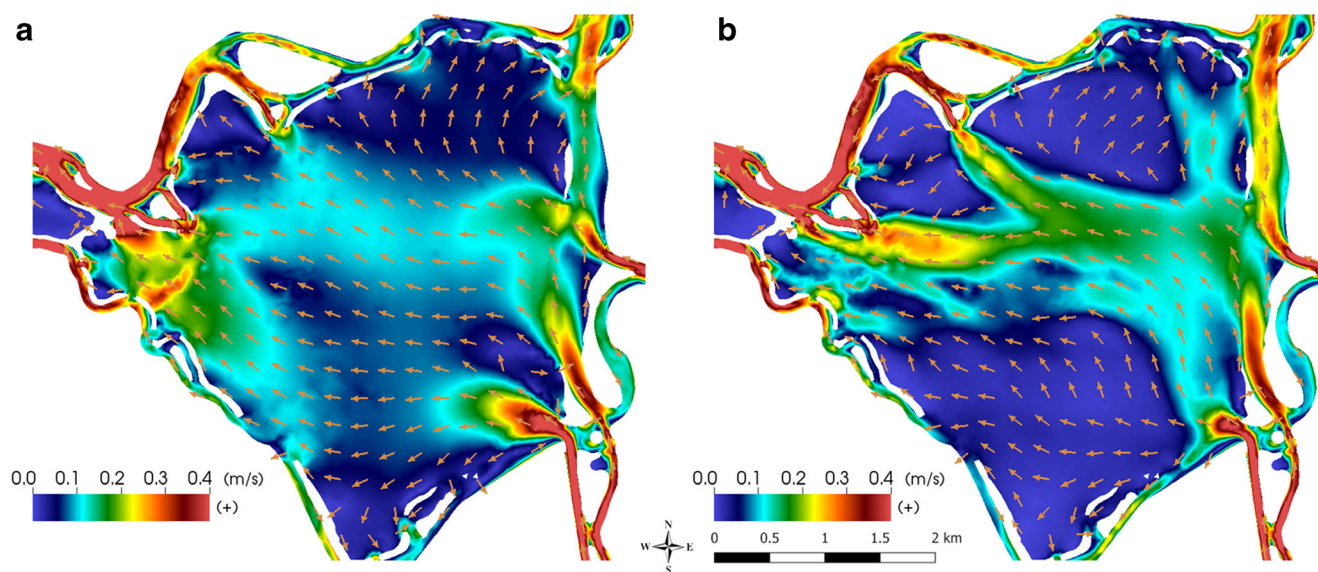


Fig. 10 Depth-averaged velocity patterns (a) without and (b) with SAV on August 2, 2009 at 05:00. Arrows describe direction and colors describe magnitude

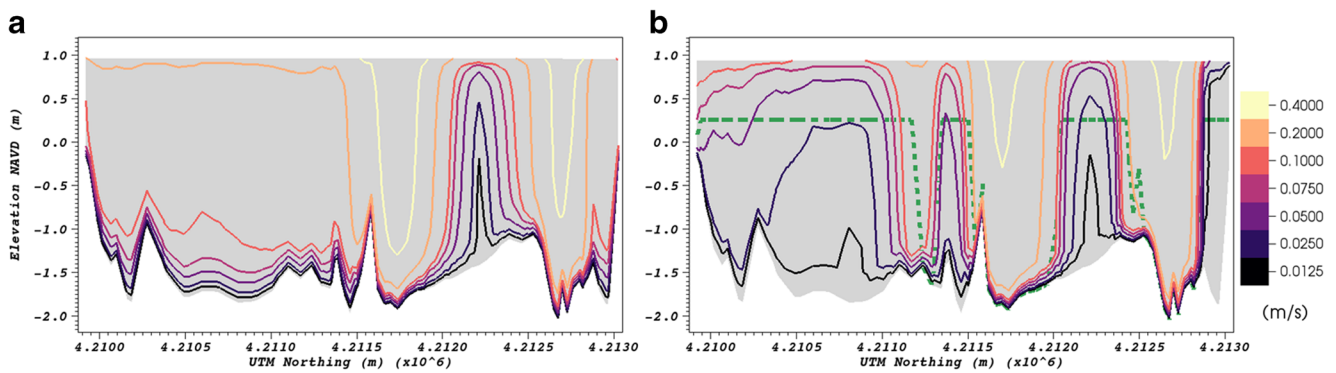


Fig. 11 Vertical profiles of the u -velocity structure on August 2, 2009 at 11:40 (flood tide), (a) without and (b) with SAV. The dashed green line in (b) indicates the canopy height

One limitation of our modeling of SAV in Franks Tract thus far is the neglect of small-scale horizontal heterogeneity in canopy height and density. Our grid elements of 15 m or larger are incapable of resolving small gaps in the vegetation patches that allow flow between them. Such gaps are visibly important when observed in the field, determining velocity patterns in the wind-driven upper layer. Further investigation is needed to determine what importance they have on flow lower in the water column or in influencing circulation at larger scales. Given the myriad difficulties of quantifying SAV at this resolution, such an approach would likely require statistical rather than deterministic fidelity to vegetation characteristics. We have also neglected the multi-species interaction and modeled the SAV only as rigid stems; some flexibility (bending) in the SAV can be modeled with a vertically variable drag coefficient, but parameterizing such a model would require assumptions beyond what field data can support. Finally, investigation of small-scale non-hydrostatic effects (Wu et al. 2007) is beyond the capability of the current model.

5.4 Discussion: comparison with previous studies

The field application presented in this section epitomizes the superior flexibility and efficiency of the new model in resolving the vegetation patches while covering a large spatial extent, so that the interaction between large- and small-scale processes can be readily examined. The grid resolution varies from a few kilometers along the coast to 15 m in Franks Tract, and the flexible vertical gridding system used (Zhang et al. 2015) provides adequate resolution near the canopy, thus ensuring that 3D processes are adequately represented in the model. In contrast, previous studies tend to focus on a small area, with boundary conditions provided by grid nesting or from another model that is unencumbered by the presence of vegetation for the sake of efficiency (e.g., Temmerman et al. 2005). Despite the high resolution used, a large time step of 90 s ensures efficiency, courtesy of the implicit treatment of all terms that place stringent stability constraints including the new vegetation-related terms. This is a very important point as strong shear is often prevalent near the vegetation canopy,

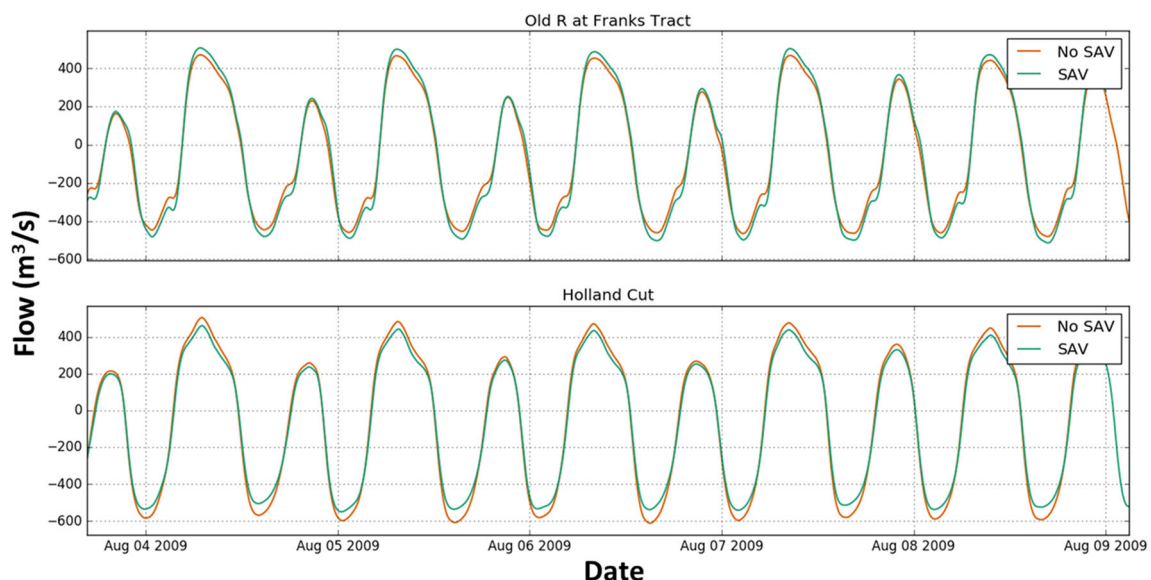


Fig. 12 Tidal discharge at Old River at Franks Tract (OSJ) and Holland Cut (HOL). Positive is in the north (ebb) direction

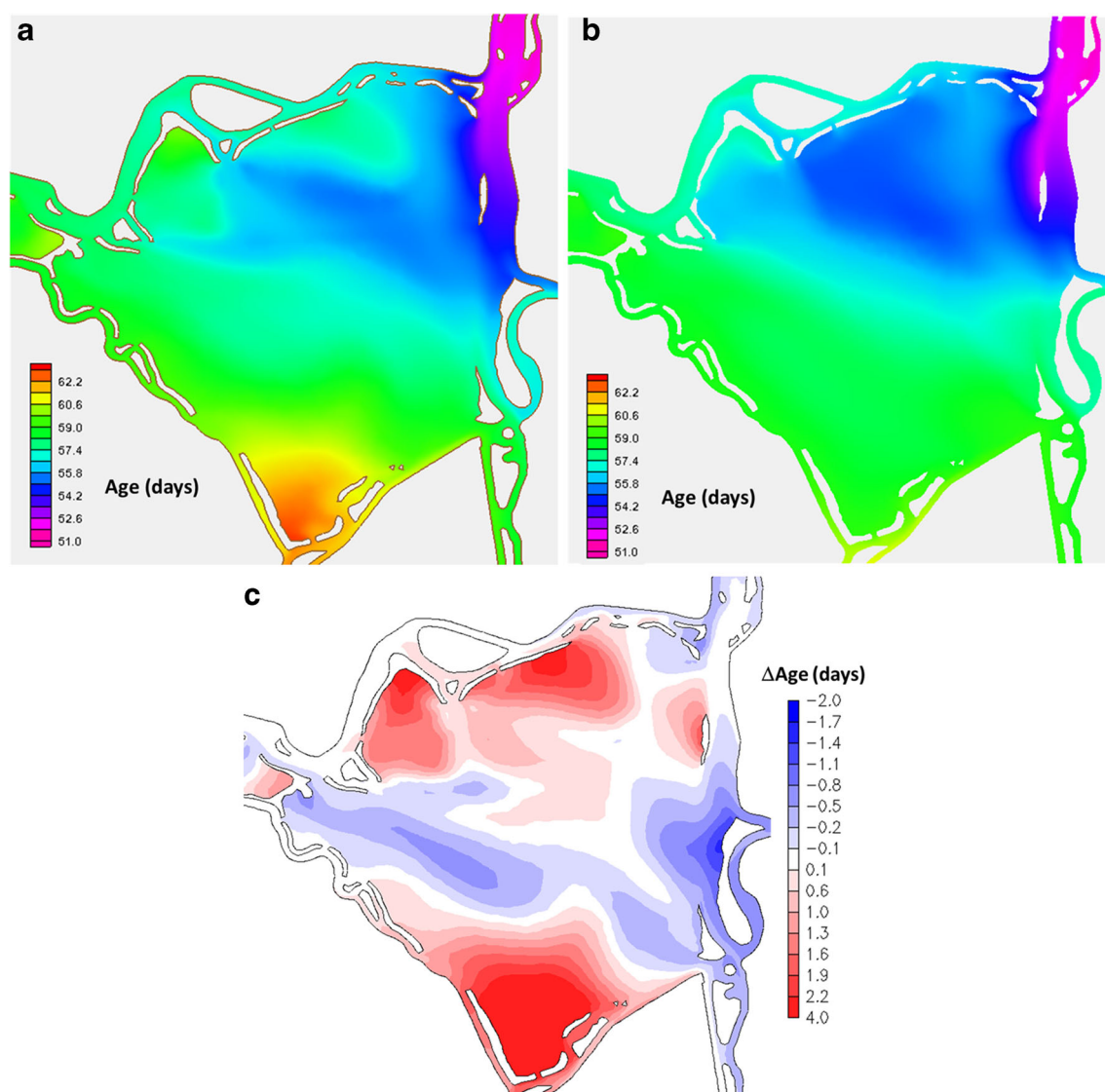


Fig. 13 Depth-averaged water age distribution in Franks Tract, averaged over 30 days from May 11 to June 10, 2009. **a** With SAV; **b** without SAV; **c** difference (**a**, **b**)

which would compromise numerical stability if an explicit scheme were used. We have also successfully tested the fully coupled current-wave setup of SCHISM to study the wave attenuation effects and confirmed that the efficiency is retained there as well. Therefore, the new model fills in a gap in realistically simulating field-scale vegetation dynamics over the long term.

The field application also touches on the challenge of characterizing the SAV itself. The scaled NDVI data we used to populate the model is available nearly at basin scale, but its applicability perhaps limited to the circumstances described here. This is different from some previous studies on emergent vegetation such as marshes (Temmerman et al. 2005), where remote sensing data may be more accurate. Alternative sampling methods used in portions of Franks Tract in later studies include hydroacoustic surveys and physical methods such as

rake samples; both methods are more limited in scale than remote sensing and neither was available for the period and extent covered by the present application.

6 Conclusions

We have developed a new 3D unstructured grid hydrostatic model that incorporates the effects of vegetation on surrounding flows. The model uses a semi-implicit time stepping method and treats the new vegetation-related terms *implicitly* to enhance numerical stability. The stability is therefore independent of the vegetation parameters, and the strong shear that can develop around the canopy can be efficiently simulated. Validation using two sets of lab data demonstrates that the new SCHISM model is capable of reasonably resolving the

complex 3D flow structure found near vegetated areas. Our results also demonstrate model's sensitivity to the bulk form drag coefficients used, which remains a major challenge in simulating vegetation effects. Application to a vegetated region in the San Francisco Bay & Delta illustrates that the vegetation causes the flow to be more channelized with stronger lateral and vertical shear. The tidal flows at two inlets are also affected by the vegetation, which strengthens the flow in one inlet and dampens it in the other. The efficiency of the new SCHISM model is particularly important for long-term studies that cover the entire lifecycle of the vegetation. The new capability that enables high-resolution simulations at large field scales for the entire lifecycle of the vegetation provides a powerful and flexible tool for coastal management and stakeholders.

Funding information This research is funded by the California Department of Water Resources. Simulations presented in this paper were conducted using the following computational facilities: (1) Sciclone at the College of William and Mary which were provided with the assistance of the National Science Foundation, the Virginia Port Authority, and Virginia's Commonwealth Technology Research Fund; (2) the Extreme Science and Engineering Discovery Environment (XSEDE; Grant TG-OCE130032), which is supported by National Science Foundation grant number OCI-1053575; (3) NASA's Pleiades.

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