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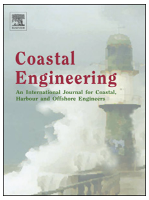

Three-dimensional hydrodynamic modeling of coastal flood mitigation by wetlands

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The mitigation of storm tides by coastal wetlands is investigated by enhancing a well-established three-dimensional hydrodynamic model to include vegetation effects on mean flow and turbulence quantities. The influence of vegetation upon the mean flow characteristics is modeled through the stem-induced form drag and inertia force incorporated into the momentum equations. Vegetative source and sink terms are added to the transport equations of the Mellor–Yamada turbulence closure model in order to properly simulate the vertical mixing process that takes place within vegetated water columns. The model adopts two well-established empirical formulas to determine the vegetation drag coefficient. Although these formulas have been established under laboratory conditions that differ from those tested in the present study, quantitative and qualitative comparisons reveal the satisfactory performance of the enhanced model to simulate complex flow–vegetation interactions. Model validation against laboratory experiments show that the vegetation-induced drag force added to the momentum equations is the main contributor to the flow-vegetation interactions. The original model that lumps the resistance due to vegetation with the bottom roughness coefficient produces locally incorrect vertical distributions of mean flow velocity and turbulence quantities. The enhanced model is applied to simulate the impacts of intertidal salt marshes of Jamaica Bay, NY, on the storm tide produced by Hurricane Irene. The model results indicate that the salt marshes played only a minimal role in mitigating the peak water elevations induced by Irene. On the other hand, the presence of the marshes causes higher velocities in non-vegetated areas such as deep channels, and lower velocities in vegetated areas, and thus redistributes energy around the bay, with likely feedbacks on water quality, marsh stability, and the response to sea level rise.

1. Introduction

Wetlands such as salt marshes are often integral components of coastal ecosystems. Wetlands provide habitat and food sources for wildlife, improve water quality, protect coastal areas from tides and storm surges, and mitigate shoreline erosion. For example, by protecting against flooding and climate instability, providing wildlife habitat and other benefits, Wisconsin's wetlands annually value between \$3.3 billion and \$152 billion to the local, regional, and national economy (Earth Economic, 2012). Costanza et al. (2008) estimated that the coastal wetlands in the US provide annually \$23.2 billion in storm protection services. Ecological, economical, and social benefits of wetlands have increased the interest among city planners and decision makers to consider coastal vegetation as green flood protection measures. Flood protection programs are increasingly leveraging numerical models to evaluate the hazard mitigation potential of wetlands (e.g. Cobell et al., 2013). Adopting an appropriate approach to simulate the complex flow–vegetation interactions is essential for the development of numerical models, particularly when utilized as decision-support tools.

The presence of vegetation in estuarine and coastal systems alters the mean flow characteristics as well as the turbulence intensity. The drag on vegetation locally decelerates the mean flow due to an increase in flow resistance. On the other hand, vegetation stems increase the turbulence intensity by converting the mean kinetic energy to turbulence kinetic energy within stem wake (Nepf, 1999). Laboratory experiments have shown that the vegetation resistance creates a shear layer at the boundary between the vegetated and non-vegetated zones (Shimizu and Tsujimoto, 1993; Nezu and Onitsuka, 2001; White and Nepf, 2008). These complex flow–vegetation interactions are neglected in most numerical models. Instead, models often simply lump the vegetation-induced resistance with the resistance due to the bottom friction. However, this approach provides little information about the mean flow and turbulence structure within the water column (Nepf, 1999). In a physics-based approach, the three-dimensional flow–vegetation interactions are modeled through vegetation-induced drag and inertia forces (Morison et al., 1950; Mendez and Losada, 2004; Li

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and Yan, 2007; Marsooli and Wu, 2014; Wu and Marsooli, 2012). In this approach, the vegetation-induced forces are considered as additional external body forces in the momentum budget as well as the budgets of turbulence quantities.

The vegetation-induced inertia force is due to the fluid acceleration around the stems. For typical flow conditions and vegetation canopies, the inertia force is much smaller than the drag force (Mendez and Losada, 2004; Henry and Myrhaug, 2013; Maza et al., 2013). The inertia force is related to the temporal acceleration of flow via the inertia coefficient, C_M. The vegetative drag force due to the viscous effect and the pressure gradient is characterized by the drag coefficient, C_D, which strongly depends on the environmental conditions, such as flow velocity, as well as the biomechanical properties of vegetation, such as stem diameter, height, and density (and, implicitly, stem flexibility). The drag coefficient can be either calibrated based on measurements or approximated based on an empirical formula. Adopting an empirical formula is beneficial in cases with insufficient data for model calibration. However, these formulas are usually developed based on laboratory experiments under limited range of flow conditions and vegetation properties. Application of such formulas to problems with different conditions requires further investigation. We dedicate parts of the present study to this topic.

Most of the coastal ocean models, such as the ADvanced CIRCulation model (ADCIRC) (Luettich et al., 1992; Wamsley et al., 2010), the Finite-Volume Community Ocean Model (FVCOM) (Chen et al., 2003), and the Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams, 2005), take the vegetation effects into account by adjusting the bottom friction. Few models have adopted the physics-based approach described above. For example, CH3D (Sheng et al., 2012) and Delft3D (Temmerman et al., 2005) include the vegetation form drag into the momentum equations. These models neglect the vegetation-induced inertia force. The turbulence closure model of CH3D, that is a simplified version of the Reynolds Stress Model (RSM), considers the effects of vegetation by adding a source term in the transport equation of turbulence kinetic energy, with a dissipation length scale which is reduced based on the vegetation canopy geometry. Delft3D uses extra terms in the transport equations of the k–ε turbulence closure model to include the influence of vegetation on vertical mixing.

In this study, the three-dimensional hydrodynamic module of an existing coastal ocean model, the Stevens Institute of Technology Estuarine and Coastal Ocean Model (sECOM), is enhanced to simulate the flow–vegetation interactions. The vegetation-induced drag and inertia forces are added to the momentum transport equations. The model's turbulence closure, that is the Mellor–Yamada 2.5 level k–l turbulence closure model, is also modified by adding vegetative source and sink terms in the transport equations of turbulence kinetic energy and turbulence length scale. To the best knowledge of the authors of this article, no previous study has modified the Mellor–Yamada turbulence closure model for vegetated coastal and oceanic systems. The adequacy of two empirical formulas to determine the vegetation drag coefficient is investigated. Moreover, the importance of the vegetative forces in the modified momentum and turbulence transport equations is quantitatively and qualitatively investigated. We also evaluate the performance of the original model that represents the vegetation-induced resistance with an increase in the bottom roughness, as done in most other 2D and 3D models to date. The model performance is assessed based on the quantitative and qualitative comparisons between measured and calculated mean flow and turbulence quantities.

The model with flow–vegetation dynamics is first tested using two laboratory experiments of flows over submerged and emergent vegetation. These test cases aim to validate the accuracy of the modeled flow–vegetation interaction, so that it can be used to simulate the larger-scale impacts of wetlands on coastal circulation and storm tides (the water level rise due to the combination of storm surge and astronomical tide). The validated model is implemented to investigate the impacts of the intertidal salt marshes of Jamaica Bay, located adjacent to the New York Harbor, on the storm tide produced by Hurricane Irene.

2. Numerical model

The numerical model enhanced in the present study is the hydrodynamic module of the Stevens Institute of Technology Estuarine and Coastal Ocean Model (sECOM). The model is a variant of the Princeton Ocean Model (POM) that was originally developed by Blumberg and Mellor (1980, 1987). sECOM is a three-dimensional, free-surface, hydrostatic, primitive equation model that has been successfully applied to oceanic, coastal, and estuarine waters (e.g. Blumberg et al., 1999; Blumberg and Georgas, 2008; Georgas, 2010; Georgas and Blumberg, 2010; Orton et al., 2012). sECOM is also the hydrodynamic module of the New York Harbor Observing and Prediction System (NYHOPS). NYHOPS, a forecasting resource for emergency preparedness in the New York City area and coastal New Jersey, is designed to provide information of meteorological and oceanographic conditions both in real-time and forecasts out to 72 h (http://stevens.edu/SSWS/).

2.1. Mean flow governing equations

The sECOM solves the Reynolds-Averaged Navier–Stokes (RANS) equations under the hydrostatic pressure assumption. In a Cartesian coordinate system the continuity and momentum equations are

$$\nabla \cdot \mathbf{V} = 0 \tag{1}$$

$$\begin{aligned}\frac{\partial u}{\partial t} + \mathbf{V} \cdot \nabla u - fv = {} & -\frac{1}{\rho} f_{veg,x} - \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(2A_M \frac{\partial u}{\partial x}\right) \\ & + \frac{\partial}{\partial y}\left(A_M\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right) + \frac{\partial}{\partial z}\left(K_M \frac{\partial u}{\partial z}\right)\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{\partial v}{\partial t} + \mathbf{V} \cdot \nabla v + fu = {} & -\frac{1}{\rho} f_{veg,y} - \frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\left(A_M\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right) \\ & + \frac{\partial}{\partial y}\left(2A_M \frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_M \frac{\partial v}{\partial z}\right)\end{aligned} \tag{3}$$

$$\rho g = -\frac{\partial p}{\partial z} \tag{4}$$

where $\mathbf{V}$ is the flow velocity vector; u, v, and w are the flow velocity components in longitudinal x, lateral y, and vertical z directions, respectively; ρ is the fluid density; p is the hydrostatic pressure; f is the Coriolis parameter; K_M is the vertical eddy viscosity; A_M is the horizontal eddy viscosity, and $f_{veg,x}$ and $f_{veg,y}$ are the vegetation-induced forces in longitudinal and lateral directions, respectively. The model considers the turbulence anisotropy through different eddy viscosities for vertical and horizontal mixing processes. The eddy viscosities are calculated from turbulence closure models described later.

The vegetation-induced forces include the form drag and inertia force. The vegetation stems are treated as cylindrical elements with diameter b_v. The vegetative forces are formulated based on Morison et al. (1950) as follows

$$f_{veg,i} = \frac{1}{2}\rho C_D N_v b_v V_i |\mathbf{V}| + \rho C_M N_v \frac{\pi b_v^2}{4}\frac{\partial V_i}{\partial t} \tag{5}$$

where the first term on the right-hand side is the vegetation-induced drag force and the second term is the inertia force. V_i is the flow velocity in i direction ($i = x$ and y), and N_v is the number of vegetation elements per unit area. The vegetation inertia coefficient C_M is constant and is set to 2 (Reeve et al., 2004, Marsooli and Wu, 2014). The sensitivity of the model to the inertia coefficient is investigated in Section 3.1. The vegetation drag coefficient C_D can be a calibration parameter, or estimated using empirical formulas such as those developed by White (2005) and Tanino and Nepf (2008), which are described later.