Ocean Modelling 110 (2017) 32–48

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Benchmarking an unstructured grid sediment model in an energetic estuary

Jesse E. Lopez*, António M. Baptista

NSF Science and Technology Center for Coastal Margin Observation & Prediction, Oregon Health & Science University, Portland, OR, USA

ARTICLE INFO

Article history:
Received 20 April 2016
Revised 9 November 2016
Accepted 13 December 2016
Available online 14 December 2016

Keywords:
Sediment model
Model validation
Sediment dynamics
Estuaries
Columbia River

ABSTRACT

A sediment model coupled to the hydrodynamic model SELFE is validated against a benchmark combining a set of idealized tests and an application to a field-data rich energetic estuary. After sensitivity studies, model results for the idealized tests largely agree with previously reported results from other models in addition to analytical, semi-analytical, or laboratory results. Results of suspended sediment in an open channel test with fixed bottom are sensitive to turbulence closure and treatment for hydrodynamic bottom boundary. Results for the migration of a trench are very sensitive to critical stress and erosion rate, but largely insensitive to turbulence closure. The model is able to qualitatively represent sediment dynamics associated with estuarine turbidity maxima in an idealized estuary. Applied to the Columbia River estuary, the model qualitatively captures sediment dynamics observed by fixed stations and shipborne profiles. Representation of the vertical structure of suspended sediment degrades when stratification is underpredicted. Across all tests, skill metrics of suspended sediments lag those of hydrodynamics even when qualitatively representing dynamics. The benchmark is fully documented in an openly available repository to encourage unambiguous comparisons against other models.

1. Introduction

Sediment dynamics of estuaries control morphodynamic and biogeochemical processes with implications ranging from ecosystem function and health (Ferguson et al., 1996) to navigation (Meade, 1972) among other aspects of system sustainability, management and operation. Driven by tides and buoyancy, estuarine circulation commonly leads to a complex vertical structure of density and currents requiring three-dimensional modeling to represent the inherently depth-varying circulation and sediment processes. As a consequence, sediment modules have been developed for existing three-dimensional circulation models including structured grid models such as Delft3D (Lesser et al., 2004) and ROMS (Warner et al., 2008) and unstructured grid models including FVCOM (Chen et al., 2003), SUNTANS (Fringer et al., 2006), and SELFE (Zhang & Baptista, 2008) and its derivative SCHISM (Zhang et al., 2016). Regardless of the grid structure and specific numerics, sediment modeling systems generally solve the advection-diffusion equation for a user-defined number of suspended sediment classes with distinct approaches for boundary conditions, interactions with bathymetry, and bed load transport.

Validation of sediment models has consisted predominantly of idealized cases with assessments against analytical or laboratory results. Open channel cases without density effects requiring reproduction of a Rouse profile are a common test to evaluate suspended sediment dynamics (Lesser et al., 2004; Pinto et al., 2012; Warner et al., 2008). The trench migration test case of van Rijn (1986) is commonly used to evaluate simulation skill for predictive bedload and morphodynamic behavior (Lesser et al., 2004; Pinto et al., 2012; Warner et al., 2008). Idealized estuarine test cases that include density effects have been used to evaluate sediment behavior in controlled conditions, but lack quantitative solutions (Burchard & Baumert, 1998; Warner et al., 2008). Validation tests inclusive of short wave effects include both laboratory experiments (Lesser et al., 2004) and comparisons against field observations (Warner et al., 2008).

Realistic applications of suspended sediment models are frequently used to study processes associated with estuarine turbidity maxima (ETM). Brenon & Hir (1999) studied the development of the Seine ETM using a single non-cohesive class with a parameterization derived from literature values. Burchard et al. (2004) used a single non-cohesive class characteristic of that system to simulate and study the Elbe ETM using GETM. Lin et al. (2003) characterized the ETM and a secondary turbidity maximum in the York River using a single non-cohesive class with other parameterizations

* Corresponding author.
E-mail address: lopezjes@ohsu.edu (J.E. Lopez).

http://dx.doi.org/10.1016/j.ocemod.2016.12.006
1463-5003/

derived from sensitivity studies. de Nijs & Pietrzak (2012) evaluated the skill of Delft3D to represent the characteristics of multiple ETMs in the stratified Rotterdam Waterway in realistic conditions using a single non-cohesive sediment size class, with the derivation of sediment parameterization details not disclosed. Ralston et al., (2012) used four non-cohesive classes with sediment parameterization based on previous studies to describe the effects of bathymetry on sediment transport in the Hudson using ROMS. In another study with multiple classes, Ralston et al., (2013) used three non-cohesive classes to study sediment dynamics along intertidal flats in the Skagit Bay using FVCOM with the parameterization derived from available observations and literature values.

The aim of this paper is to validate an unstructured grid sediment model coupled to SELFE through a combination of idealized test cases (barotropic open channel, barotropic trench migration, and baroclinic tidally driven estuary) and a realistic application to an energetic estuary. The idealized tests are drawn from literature, and are designed to assess model skill at representing essential processes: suspended sediment transport, erosion and deposition, bed load transport, and morphological evolution. Model sensitivity to hydrodynamic and sediment parameterizations are described and optimal results are qualitatively compared against previous work and available analytical, semi-analytical, or laboratory results. Field observations from endurance stations and shipborne instrumentation in Columbia River estuary, USA are used to assess model skill in representing observed sediment dynamics in the complex and energetic Columbia River estuary. To facilitate future model inter-comparison and to promote the improvement in skill of sediment models, the tests and data are publically available as a benchmark (Lopez & Baptista, 2016).

2. Methods

2.1. Hydrodynamics model

SELFE (Zhang & Baptista, 2008) solves the Reynolds-averaged Navier–Stokes equations using both hydrostatic and Boussinesq assumptions. The governing equations are solved in a semi-implicit finite element (P_1–P_{NC}) framework using a combination of numerical methods. The advection of momentum is solved with a semi-Lagrangian method following Casulli & Cheng (1992). Scalar transport is solved using either upwind or total variation diminishing (TVD) Eulerian finite volume methods. Beyond the intrinsic differences between upwind and TVD, in SELFE the upwind scheme includes an implicit calculation of vertical flux, whereas TVD utilizes an explicit calculation resulting in a much slower time to solution. Comparisons of upwind and TVD transport schemes reveal minor differences in model skill of temperature and salinity in the Columbia River estuary. Because of the minor differences in skill and large differences in computational cost, we chose to use the much faster upwind scheme. Governing equations are closed by the general length scale (GLS) equations (Umlauf & Burchard, 2005) implemented in either a native SELFE implementation or by on-line coupling the GOTM library. The domain is discretized using a triangular, unstructured mesh in the horizontal similar to a hybrid CD grid and a hybrid Z- and S-level approach in the vertical.

In this paper, we discuss the implications of two distinct treatments for the solution of the momentum equation at the bottom boundary on represented sediment dynamics. As is common in coastal hydrodynamic models, SELFE uses a bottom boundary condition where the internal Reynolds stress is balanced with the stress from bottom friction

$$\boldsymbol{\nu}\frac{\partial \boldsymbol{u}}{\partial \boldsymbol{z}} = \boldsymbol{\tau_b} \tag{1}$$

where ν is the vertical eddy viscosity, u is the velocity, z is the vertical coordinate, and τ_b is the bottom stress. Assuming a turbulent boundary layer, a logarithmic velocity profile in the bottom boundary layer, and using turbulence closure theory to find the eddy viscosity results in a constant Reynolds stress in the bottom boundary layer:

$$\boldsymbol{\nu}\frac{\partial \boldsymbol{u}}{\partial \boldsymbol{z}} = \frac{\boldsymbol{\kappa}_0}{\boldsymbol{ln}(\boldsymbol{\delta_b}/\boldsymbol{z_o})}\sqrt{\boldsymbol{C_D}}|\boldsymbol{u_b}|\boldsymbol{u_b} \tag{2}$$

where C_d is the drag coefficient, z_0 is the bottom roughness, κ_0 is the von Karman, δ_b is the thickness of the computational cell, and $\boldsymbol{u_b}$ is the bottom velocity (Zhang & Baptista, 2008). Specifically, $\boldsymbol{u_b}$ is taken to be the velocity at the top of the bottommost computational cell. Traditionally in SELFE, the discretized momentum equation was solved from the free surface to the top of the bottommost computational cell with the bottom node assigned a velocity of 0 to be consistent with a log layer adhering to the law of the wall. A new implementation, starting with version 4.0 of SELFE, solves the momentum equation from the surface to the bottom node to be consistent with the finite element formulation resulting in a non-zero velocity at the bottom node and an improved representation of the bottom boundary layer. The two implementations produce distinct estimates of $\boldsymbol{u_b}$ used in Eq. (2) resulting in distinct representations of bottom stress and shear. The implications of the new bottom boundary treatment of momentum for sediment modelling are discussed in idealized test cases. For convenience in differentiation, we refer to the traditional implementation as "no-slip" and the newer treatment as "slip" recognizing that formally both treatments are partial slip conditions.

2.2. Sediment model

The sediment model evaluated here is derived from the Community Sediment Transport Model (CSTM) (Warner et al., 2008). The non-cohesive classes, bed property changes, and bed morphology from the CSTM model were ported by Pinto et al., (2012) to work with the unstructured grids and methods used in SELFE. The model used here is algorithmically similar to Pinto et al., (2012), but was substantially refactored to align more closely with the original CSTM implementation. Minor implementation changes to improve stability including limiting slopes and increasing checks for numerically undefined numbers were required for the model to work in the Columbia River domain.

The sediment model solves for the time evolution of suspended sediments in three-dimensions and morphological changes. Specifically, the model calculates the vertical settling, bed load transport, and interactions with the bed through erosion and deposition for a user-defined number of non-cohesive classes. Suspended sediment concentrations are calculated by solving the advection-diffusion equation with additional terms for settling velocity and horizontal velocity

$$\frac{\partial \boldsymbol{C_n}}{\partial \boldsymbol{t}} + \boldsymbol{u}\frac{\partial \boldsymbol{C_n}}{\partial \boldsymbol{x}} + \boldsymbol{v}\frac{\partial \boldsymbol{C_n}}{\partial \boldsymbol{y}} + \boldsymbol{w}\frac{\partial \boldsymbol{C_n}}{\partial \boldsymbol{z}} = \frac{\partial}{\partial \boldsymbol{z}}\left(\boldsymbol{\kappa}\frac{\partial \boldsymbol{C_n}}{\partial \boldsymbol{z}}\right) + \boldsymbol{w_{s,n}}\frac{\partial \boldsymbol{C_n}}{\partial \boldsymbol{z}} + \boldsymbol{F_h} \tag{3}$$

where C_n is the sediment concentration of class n, $(u,\ v,\ w)$ are the directional velocity components, κ is the eddy diffusivity, $w_{s,\,n}$ is the settling velocity of class n, and F_h is the horizontal diffusion. Eq. (3) is solved using either the upwind or TVD transport schemes in SELFE (Zhang & Baptista, 2008). The vertical movement of sediment is handled using a hybrid WENO-PPM semi-Lagrangian method (Warner et al., 2008). Multiple bed layers are supported and erosional flux is calculated using the method outlined by Harris & Wiberg (2001). Specifically, the depositional flux, D_n, is calculated using

$$\boldsymbol{D_n} = \boldsymbol{w_{s,n}} \cdot \boldsymbol{C_b} \tag{4}$$