Estuarine, Coastal and Shelf Science 93 (2011) 228–238

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

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

Numerical modeling of hyperpycnal flows in an idealized river mouth

Yan Wang [a], Houjie Wang [a,b,c,*], Naishuang Bi [a,b], Zuosheng Yang [a,b]

[a] College of Marine Geosciences, Ocean University of China, 238 Songling Rd., Qingdao 266100, China
[b] Key Laboratory of Submarine Sciences and Prospecting Technique, Ministry of Education, 238 Songling Rd., Qingdao 266100, China
[c] State Key Laboratory of Estuarine and Coastal Research (SKLEC), East China Normal University, 3663 Zhongshan N. Rd., Shanghai 200062, China

ARTICLE INFO

Article history:
Received 5 February 2010
Accepted 16 February 2011
Available online 2 March 2011

Keywords:
hyperpycnal flows
suspended sediment transport
settling velocity
tidal mixing
numerical modeling

ABSTRACT

Numerical experiments in an idealized river mouth are conducted using a three-dimensional hydrodynamics model (EFDC model) to examine the impacts of suspended sediment concentration (SSC), settling velocity of sediment and tidal mixing on the formation and maintenance of estuarine hyperpycnal flows. The standard experiment presents an illustrative view of hyperpycnal flows that carry high-concentrated sediment and low-salinity water in the bottom layer (>1.0 m in thickness) along the subaqueous slope. The structure and intra-tidal variation of the simulated hyperpycnal flows are quite similar to those previously observed off the Huanghe (Yellow River) mouth. Results from the three control experiments show that SSC of river effluents is the most important parameter to the formation of hyperpycnal flows. High SSC will increase the bulk density of river effluents and thus offset the density difference between freshwater and seawater. Low SSC of river effluents will produce a surface river plume, as commonly observed in most large estuaries. Both the settling velocity of sediment particles and the tidal mixing play an important role in maintaining the hyperpycnal flows. Increasing settling velocity enhances the deposition of sediment from the hyperpycnal layer and thus accelerates the attenuation of hyperpycnal flows, whereas increasing tidal mixing destroys the stratification of water column and therefore makes the hyperpycnal flows less evident. Our results from numerical experiments are of importance to understand the initiation and maintenance of hyperpycnal flows in estuaries and provide a reference to the rapidly decaying hyperpycnal flows off the Huanghe river mouth due to climatic and anthropogenic forcing over the past several decades.

1. Introduction

When a river with extremely high suspended sediment concentration (SSC) flows into an estuary, the river effluents will be probably much denser than that of the ambient ocean water. As a result, the river water carrying suspended sediment will plunge beneath the oceanic water and generate hyperpycnal flows (Bates, 1953; Wright et al., 1988; Mulder and Syvitski, 1995; Wright and Nittrouer, 1995). In the estuaries of many small to medium size rivers, the hyperpycnal flows generate mostly during flood seasons or during some episodic events including jÖkulhaups, dam breaking and draining, and lahars (Wright et al., 1988; Mulder et al., 2003), when the SSC of the river water are at least 35–45 kg/m^3 depending upon the density of the ambient water (Mulder and Syvitski, 1995). The main hydrodynamic factor for the generation of hyperpycnal flow is the negative buoyant effect caused by the density contrast between the river effluents and the ambient ocean water (Wright and Nittrouer, 1995). Hyperpycnal flows can travel along the slope for hours to weeks until its higher density disappears when most of the sediment deposits on the seabed from the hyperpycnal layer (Mulder and Syvitski, 1995). By transporting and depositing a large amount of sediments that are closely tied terrestrial elements as well as metal contamination in particulate form, hyperpycnal flows in estuaries play an important role in estuarine morphology and coastal biogeochemical cycle in marine environment.

Most direct observations of hyperpycnal flows were from freshwater of lakes (Gould, 1951; Lambert et al., 1976; Nelson et al., 1999) and reservoirs (Wiebe, 1939; Ford and Johnson, 1983). In marine environment, it has long been postulated that hyperpycnal flows exist in the estuaries of high turbid rivers and small mountainous rivers (Mulder and Syvitski, 1995; Milliman and Kao, 2005; Milliman et al., 2007); however, most of our knowledge about hyperpycnal flows in marine environment comes either from the inference of the sedimentary records on the continental shelves (e.g., Foster and Carter, 1997; Mulder et al., 1997; Normark et al., 1998) or from the observations of hyperpycnal discharges during extreme events (e.g., Milliman and Kao, 2005; Milliman et al., 2007). Thus, there is a lack of knowledge about the process and mechanism of hyperpycnal flows in estuaries, because it is hard to monitor such process on site

* Corresponding author. College of Marine Geosciences, Ocean University of China, 238 Songling Rd., Qingdao 266100, China.
E-mail address: hjwang@mail.ouc.edu.cn (H. Wang).

0272-7714/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ecss.2011.02.011

due to its unpredictable nature. Although the critical concentration for a hyperpycnal discharge from river was estimated as >36 kg/m^3 (e.g., Mulder and Syvitski, 1995), it is, however, still unclear that which factors are dominant for the formation and maintenance of hyperpycnal flows in estuaries.

Given the operational difficulty for *in-situ* observations in estuaries, numerical model can be considered as an effective means to advance our understanding on the processes of hyperpycnal flows. Among previous numerical approaches for estuarine sediment transport, several factors were discussed in detail for the studies of the hyperpycnal flows. Khan et al. (2005) used a numerical model to simulate hyperpycnal events and their interaction with the alongshore current, the results of which indicate that the alongshore current has significant impacts to the spreading and deposition pattern of hyperpycnal flow. Wright et al. (2001) suggested that the ambient waves and currents can enhance the turbulence in the water, and finally constrain the generation of hyperpycnal flow unless the SSC of the flow is high enough. Wang and Wang (2010) compared the numerical results and observations in the Huanghe (Yellow River) estuary, and concluded that the tidal straining effect can strengthen the sediment-induced stratification during flood tide, and thus produce an evidently turbid bottom layer with SSC much higher than that during ebb flood. In this paper, a three-dimensional hydrodynamics model with suspended sediment transport (Environmental Fluid Dynamics Code, EFDC) was applied to simulate the process of sediment transport in an idealized river mouth with high SSC. The main purpose is to examine the controlling factors for the formation and maintenance of estuarine hyperpycnal flows through several numerical experiments.

2. Model description

The EFDC model, originally developed by the Virginia Institute of Marine Science (Hamrick, 1992), is a multipurpose three-dimensional hydrodynamic modeling package for simulating a diverse range of environmental flow and transport problems. It solves the three-dimensional, vertically hydrostatic, free surface, turbulent averaged equations of motions for a variable density fluid. It uses orthogonal-curvilinear or Cartesian horizontal coordinates and a stretched sigma grid in vertical dimension. Dynamically coupled transport equations for turbulent kinetic energy, turbulent length scale, salinity and temperature are also solved. Mellor and Yamada (1982) level 2.5 turbulence closure scheme, modified by Galperin et al. (1988), was used in the two turbulence parameter transport equations. An externally specified high frequency surface gravity wave field was used in the optional bottom boundary layer submodel to implement the wave–current interaction within the boundary layer. The physics of the EFDC model and many aspects of the computational scheme are equivalent to the widely used Princeton Ocean Model (Blumberg and Mellor, 1987).

The transport equation for suspended sediment is described as follows:

$$\partial_t(HC) + \partial_x(HuC) + \partial_y(HvC) + \partial_z(wC) - \partial_z(w_sC) = \partial_x(K_H H\partial_x C) + \partial_y(K_H H\partial_y C) + \partial_z\left(\frac{K_V}{H}\partial_z C\right) + Q_S^E + Q_s^I \tag{1}$$

where C represents the suspended sediment concentration (kg/m^3), u and v are the horizontal velocity components in the dimensionless curvilinear-orthogonal horizontal coordinates x and y. w is the vertical velocity in the stretched vertical coordinate z. K_H is the horizontal diffusivity determined by the Smagoringsky scheme (Smagoringsky, 1963). K_V is the vertical eddy diffusivity estimated by the Mellor–Yamada level 2.5 turbulence closure scheme (Mellor and Yamada, 1982; Galperin et al., 1988). w_s represents the settling velocity of sediment particles. The source-sink term has been split into an external part (Q_S^E), including point and non-point sources of sediment loads, and an internal part (Q_S^I) including reactive decay of organic sediments or the exchange of mass between sediment classes if formation and destruction of flocs were simulated.

Settling velocity (w_s) of sediment particles is experimentally determined in laboratory, but it is usually impacted by many other factors besides its size such as fluid density, turbulence and flocculation induced by chemical or biological processes (Shi and Zhou, 2004; Fennessy et al., 2006). Given the effect of suspended sediment concentration on settling of sediment particle (e.g., van Rijn, 1993), the settling velocity is empirically determined by the initial settling velocity in still water (w_{s0}) and suspended sediment concentration, as follows:

$$w_s = w_{s0}\left(C/C_f\right)^\alpha \tag{2}$$

where w_{s0} is the settling velocity in still water that is directly related to the size and shape of sediment particle. C_f is the referential concentration and α is an empirical constant.

2.1. The vertical boundary conditions for suspended sediment transport equation are defined as

At the seabed, $z \to 0$, the net sediment flux is equal to the summation of sediment erosion flux and sediment deposition flux. At the water surface, $z \to 1$, there is no net transport across the free surface.

$$\begin{aligned} -\frac{K_v}{H}\partial_z C - w_s C &= J_0^r - J_0^d : \quad z \to 0 \\ -\frac{K_v}{H}\partial_z C - w_s C &= 0 \qquad\quad : \quad z \to 1 \end{aligned} \tag{3}$$

where J_0^r is the flux of sediment eroded from the bed (resuspension) and J_0^d is the flux of sediment deposited to the bed (kg m^{-2} s^{-1}). The net exchange flux between water column and seabed is controlled by the near-bed flow environment and the geomechanics of the deposited bed. When the near-bed shear stress (τ_b) exerted by the flow decreases below the critical stress for deposition (τ_{cd}), deposition happens. The sediment deposition flux is expressed by the following formula:

$$J_0^d = \begin{cases} -w_s C\left(\dfrac{\tau_{cd} - \tau_b}{\tau_{cd}}\right) & : \tau_b \le \tau_{cd} \\ 0 & : \tau_b \ge \tau_{cd} \end{cases} \tag{4}$$

When the near-bed shear stress (τ_b) increases above the critical stress for erosion (τ_{cr}), the seabed is eroded, and the sediment erosion flux is described as follows:

$$J_0^r = \begin{cases} \dfrac{dm_e}{dt}\left(\dfrac{\tau_b - \tau_{ce}}{\tau_{ce}}\right)^\alpha & : \tau_b \ge \tau_{cr} \\ 0 & : \tau_b \le \tau_{cr} \end{cases} \tag{5}$$

where $\dfrac{dm_e}{dt}$ is the erosion rate per unit surface area of the seabed and α is empirical parameter generally derived from laboratory experiments or *in-situ* observations. The critical depositional stress (τ_{cd}) and critical erosional stress (τ_{cr}) are prescribed parameters in the model.

The near-bed shear stress τ_b (kg m^{-1} s^{-2}) is related to the bottom velocity by the quadratic resistance formulation:

$$\tau_b = \rho C_d |U_b| U_b \tag{6}$$

where U_b is the bottom frictional velocity. C_d is the bottom stress coefficient, given by: