Advances in Water Resources 31 (2008) 1004–1014

Contents lists available at ScienceDirect

Advances in Water Resources

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

Three-dimensional numerical modeling of cohesive sediment transport and wind wave impact in a shallow oxbow lake

Xiaobo Chao [a,*], Yafei Jia [a], F. Douglas Shields Jr. [b], Sam S.Y. Wang [a], Charles M. Cooper [b]

[a] National Center for Computational Hydroscience and Engineering, University of Mississippi, Carrier Hall 102, University, MS 38677, United States
[b] National Sedimentation Laboratory, U.S. Department of Agriculture, Agricultural Research Service, Oxford, MS 38655, United States

ARTICLE INFO

Article history:
Received 12 December 2007
Received in revised form 3 April 2008
Accepted 11 April 2008

Keywords:
3D numerical model
Cohesive sediment
Wind-driven current
Wind-induced wave
Oxbow lake

ABSTRACT

It was observed that in some closed inland lakes sediment transport was dominated by wind-induced currents, and the sediment resuspension was primarily driven by wind-induced waves. This paper presents the development and application of a three-dimensional numerical model for simulating cohesive sediment transport in water bodies where wind-induced currents and waves are important. In the model, the bottom shear stresses induced by currents and waves were calculated, and the processes of resuspension (erosion), deposition, settling, etc. were considered. This model was first verified by a simple test case consisting of the movement of a non-conservative tracer in a prismatic channel with uniform flow, and the model output agreed well with the analytical solution. Then it was applied to Deep Hollow Lake, a small oxbow lake in Mississippi. Simulated sediment concentrations were compared with available field observations, with generally good agreement. The transport and resuspension processes of cohesive sediment due to wind-induced current and wave in Deep Hollow Lake were also discussed.

1. Introduction

Sediment has been identified as one of the leading nonpoint-source pollutants in the United States. Sediments in shallow lakes influence physical and chemical processes in the water column. Suspended sediment reduces light penetration needed for the growth of phytoplankton. In addition, nutrients may interact with suspended sediment through the processes of adsorption and desorption.

The basic processes involved in cohesive sediment transport, such as flocculation, deposition, erosion, etc., have been studied by many scientists. Burban et al. [2] presented a formula to calculate the settling velocity of flocs in fresh water based on laboratory experiments. Thorn [39], Ziegler and Nisbet [47], Li and Mehta [23] established several empirical formulas for settling velocity of flocs by considering the effects of sediment size, sediment concentration, salinity, turbulence intensity, and bed shear stress. Krone [22] and Mehta and Partheniades [29] investigated deposition of cohesive sediment and proposed formulas to estimate deposition rates. Partheniades [32] proposed a formula to calculate the erosion rate of cohesive sediment.

Jin and Sun [19] studied the flow circulation, wave dynamics and their impacts on sediment resuspension and vertical mixing in Lake Okeechobee based on field measurements. Their results show that wave action is the dominant factor in sediment resuspension in that lake. Cozar et al. [6] presented empirical correlations between total turbidity and wind speed based on the field observations. They also obtained an empirical formula to calculate the suspended sediment concentration using wind speed and water depth.

In recent decades, some researchers have studied the cohesive sediment transport in rivers, lakes, and coastal waters using numerical models. Willis and Krishnappan [43] reviewed a number of numerical models and gave an overview of the knowledge base required for modeling cohesive sediment transport in river flow. Nicholson and O'connor [30] developed a 3D cohesive sediment transport model using a splitting method in conjunction with a characteristics technique and a mixed explicit–implicit finite difference approach. Ziegler and Nisbet [47], Bailey and Hamilton [1], and Wu and Wang [45] developed several two-dimensional (2D) depth-averaged models to simulate cohesive sediment transport. Liu [25] developed a vertical (laterally integrated) two-dimensional model to simulate the cohesive sediment transport in Danshuei River estuary by considering the effects of reservoir construction at the upstream of the river. Normant [31], Jin and Ji [18] proposed 3D layer models to simulate the cohesive sediment transport in estuaries and lake, respectively.

Some researchers have shown that sediment resuspension in shallow lakes is primarily a result of wave action [28,12]. Field observations in Deep Hollow Lake, a shallow oxbow lake in Mississippi showed that during the period from October to December of

* Corresponding author. Tel.: +1 662 9156564; fax: +1 662 9157796.
E-mail address: chao@ncche.olemiss.edu (X. Chao).

0309-1708/$ - see front matter
doi:10.1016/j.advwatres.2008.04.005

1999, the concentration of suspended sediment in the lake varied from 20 to 90 mg/l, even though there was no runoff discharged into the lake during this time [33]. It was postulated that these levels of suspended sediment concentration reflected the influence of wind-induced currents and waves.

In this study a 3D model was developed based on the mass transport equation to simulate the concentration distribution of cohesive sediment in shallow lakes. It was assumed that low concentration of sediment does not affect the motion of flow, therefore, the decoupled approach was used to calculate the flow field and sediment transport separately. Flow information such as velocities, water surface elevations, and eddy viscosity parameters were obtained from a three-dimensional hydrodynamic model CCHE3D [15], and processes of flocculation, deposition, and erosion were considered in the cohesive sediment transport simulation. The wind-driven processes were considered as important features for sediment transport and resuspension. The model was first tested using an analytical solution for the transport of non-conservative substance in open channel flow, and then it was applied to simulate distribution of cohesive sediment in Deep Hollow Lake.

2. Model description

2.1. Governing equations

To study the cohesive sediment transport in shallow lakes, a numerical model was developed based on CCHE3D hydrodynamic model [15,16]. CCHE3D is a three-dimensional model that can be used to simulate unsteady turbulent flows with irregular boundaries and free surfaces. It is a finite element model utilizing a special method based on the collocation approach called the efficient element method. This model has been successfully applied to analyze wind-driven flow, turbulent flow fields in scour holes and around a submerged training structure in a meander bend [15,4].

The governing equations of the three-dimensional unsteady hydrodynamic model can be written as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu\frac{\partial u_i}{\partial x_j} - \overline{u_i'u_j'}\right) + f_i \tag{2}$$

where u_i (i = 1, 2, 3) = Reynolds-averaged flow velocities (u, v, w) in Cartesian coordinate system (x, y, z); t = time; ρ = water density; p = pressure; ν=fluid kinematic viscosity; $-\overline{u_i'u_j'}$ = Reynolds stress; and f_i = body force terms.

The free surface elevation (η) is computed using the following equation:

$$\frac{\partial \eta}{\partial t} + u_f\frac{\partial \eta}{\partial x} + v_f\frac{\partial \eta}{\partial y} - w_f = 0 \tag{3}$$

where u_f, v_f and w_f = velocities at the free surface; η = surface water elevation.

Wind stress is one of the most important driving forces for lake water movement. The wind shear stresses (τ_{wx} and τ_{wy}) at the free surface are expressed by

$$\tau_{wx} = \rho_a C_d U_{wind}\sqrt{U_{wind}^2 + V_{wind}^2} \tag{4}$$

$$\tau_{wy} = \rho_a C_d V_{wind}\sqrt{U_{wind}^2 + V_{wind}^2} \tag{5}$$

where ρ_a = air density; U_{wind} and V_{wind} = wind velocity components at 10 m elevation in x and y directions, respectively. Although the drag coefficient C_d may vary with wind speed [21,17], for simplicity, many researchers assumed the drag coefficient was a constant on the order of 10^{-3} [14,1,46,48,34,20]. In this study, C_d was set to 1.0×10^{-3}, and this value is applicable for simulating the wind-driven flow in Deep Hollow Lake [4].

The governing equation for cohesive sediment transport is based on the three-dimensional mass transport equation:

$$\frac{\partial C}{\partial t} + \frac{\partial (uC)}{\partial x} + \frac{\partial (vC)}{\partial y} + \frac{\partial (w - w_s)C}{\partial z} = \frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z\frac{\partial C}{\partial z}\right) \tag{6}$$

in which C = concentration of cohesive sediment; D_x, D_y and D_z = mixing coefficients in x, y and z directions, respectively; and w_s = settling velocity.

2.2. Settling velocity

The settling velocity of cohesive sediment depends on the floc size, concentration of particles and organic content of the sediment. The flocculation process is dynamic and complex. The median floc diameter can be estimated from the following experimentally based equation [9,24]:

$$d_m = \left(\frac{\alpha_0}{CG}\right)^{0.5} \tag{7}$$

where d_m = median floc diameter (cm); G = fluid shear stress (dyne/cm^2); C = concentration of sediment (g/cm^3); and α_0 = experimentally determined constant. For fine-grained cohesive sediments in freshwater, $\alpha_0 = 10^{-8}$ g^2/ cm^3/s^2.

Based on laboratory experiments on flocculated, cohesive sediments in freshwater, Burban et al. [2] proposed a formula to calculate the settling velocity:

$$w_s = a d_m^b \tag{8}$$

where $a = 9.6 \times 10^{-4}\ (CG)^{-0.85}$ and $b = -\lfloor 0.8 + 0.5\log\ (CG - 7.5 \times 10^{-6})\rfloor$

Eqs. (7) and (8) address the effects of sediment concentration and flow shear stress on flocculation, and they can be used for lake simulation.

2.3. Boundary conditions

To solve the 3D cohesive sediment transport Eq. (6), the boundary conditions at the free surface and bottom are needed. At the free surface, the vertical sediment flux is zero and the following condition is applied:

$$w_s C + D_z\frac{\partial C}{\partial z} = 0 \tag{9}$$

At the bottom, the following condition is applied:

$$w_s C + D_z\frac{\partial C}{\partial z} = D_b - E_b \tag{10}$$

where D_b and E_b = deposition rate and erosion (resuspension) rate at bottom, respectively (kg/m^2/s).

Based on Krone [22] and Mehta and Partheniades [29], the deposition rate can be calculated by:

$$D_b = \begin{cases} 0 & \tau_b > \tau_{cd} \\ w_s C\left(1 - \dfrac{\tau_b}{\tau_{cd}}\right) & \tau_b \leqslant \tau_{cd} \end{cases} \tag{11}$$

Erosion rate is generally expressed as Partheniades [32]

$$E_b = \begin{cases} 0 & \tau_b < \tau_{ce} \\ M\left(\dfrac{\tau_b}{\tau_{ce}} - 1\right) & \tau_b \geqslant \tau_{ce} \end{cases} \tag{12}$$

where τ_b = bed shear stress (N/m^2); τ_{cd} = critical shear stress for deposition (N/m^2); M = erodibility coefficient relating to the sediment properties, the reported values are in the range of 0.00001–0.0004 kg/m^2/s [41]; τ_{ce} = critical shear stress for erosion (N/m^2).