DEVELOPMENT AND APPLICATION OF NCCHE'S SEDIMENT TRANSPORT MODELS

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ABSTRACT

The governing equations, model closures, empirical functions and numerical methods of sediment transport models developed in NCCHE are briefly reviewed in this paper. Several verification and application examples are selected to demonstrate the capabilities of NCCHE's models.

1. INTRODUCTION

Since its establishment in 1982, the National Center for Computational Hydroscience and Engineering (NCCHE) at the University of Mississippi has developed a variety of sediment transport models, including CCHE1D, CCHE2D, CCHE3D, and several other internal research models. These models have been extensively tested and widely applied to the solution of many real-life projects in hydraulic, agricultural, and environmental engineering. Briefly presented here are their main features. More details can be found in related journal and conference articles, technical reports, and user's manuals.

2. GOVERNING EQUATIONS

The phenomena of flow and sediment transport in rivers are characterized by turbulence, freesurface variation, bed change, phase interaction, etc. In the time being, it is very difficult to include all of these effects accurately in a model for solving practical engineering problems. Therefore, NCCHE's sediment transport models adopt the following assumptions:

(a) Sediment concentration is low enough so that the hydrodynamics of the flow is not affected by the sediment movements. Therefore, the clear-water flow and the sediment advection-diffusion equations are solved separately or decoupled.

(b) The time scale of bed change is much larger than that of flow movement. Therefore, at each time step the flow is calculated assuming a "fixed" bed.

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(c) Interactions among different size classes of moving sediment are ignored. Thus the transport of each size class of sediment is handled individually. However, the hiding and exposure mechanism in nonuniform bed material is considered through the introduction of correction factors in the nonuniform sediment transport capacity formulas.

(d) Empirical functions for sediment transport capacities, channel roughness coefficients, constants in the turbulence models, etc. are adopted to close the mathematical model into numerical-empirical model to conduct computational simulation.

Based upon the above assumptions, CCHE1D, 2D and 3D models for free-surface flow and sediment transport in general situations have been developed (Jia and Wang, 1999; Jia et al., 2001; Wu et al., 2004; Wu, 2004). However, for special cases such as sediment transport under dam-break and levee-breach flows, NCCHE has developed more complex models that denounce the above assumptions (a) and (b) and take into account the interactions among flow, sediment transport, and bed change (Wu and Wang, 2005).

2.1 CCHE1D Model Equations

The CCHE1D model computes the flow in dendritic channel networks with instream hydraulic structures by solving the St. Venant equations. CCHE1D calculates the non-equilibrium transport of non-uniform total-load sediment, which is governed by (Wu et al., 2004)

$$\frac{\partial (AC_{lk})}{\partial t} + \frac{\partial Q_{lk}}{\partial x} + \frac{1}{L_s} (Q_{lk} - Q_{l^{*k}}) = q_{lk} \quad (k=1, 2, \dots, N)$$
(1)

where t is the time; x is the longitudinal coordinate; A is the cross-sectional area of the flow; C_{tk} is the section-averaged total-load sediment concentration; Q_{tk} is the actual sediment transport rate; Q_{t^*k} is the sediment transport capacity or the so-called equilibrium transport rate; L_s is the nonequilibrium adaptation length of sediment transport; q_{lk} is the side inflow or outflow sediment discharge from bank boundaries or tributary streams per unit channel length; each index k represents a sediment size class; and N is the total number of size classes.

The bed deformation due to size class k is determined with

$$\left(1-p'\right)\left(\frac{\partial A_b}{\partial t}\right)_k = \frac{1}{L_s}\left(Q_{tk}-Q_{t^*k}\right) \quad (k=1,\,2,\ldots,N)$$
(2)

where p' is the bed material porosity; A_b is the cross-sectional area of the bed above a reference datum; and $(\partial A_b / \partial t)_b$ is the bed deformation rate caused by size class k.

The sediment transport capacity is determined by several well-tested empirical formulas given in Section 3.4. These formulas are written in a general form as

$$Q_{t^*k} = p_{bk}Q_{tk}^*$$
 (k=1, 2,..., N) (3)

where p_{bk} is the availability factor of the *k*th size class of sediment, which is defined here as the percentage of size class *k* in the mixing layer of bed material; and Q_{tk}^* is the potential sediment transport capacity of size class *k*.

To account for the variation of bed material gradation in time and space, the bed material is divided into several layers at each computational node. The surface layer is the mixing layer that directly participates in the exchange with the sediment moving with the flow. According to mass balance, the following equation for the variation of bed material gradation in the mixing layer was derived (see Wu et al., 2004)

$$\frac{\partial(\delta_m p_{bk})}{\partial t} = \left(\frac{\partial z_b}{\partial t}\right)_k + p_{bk}^* \left(\frac{\partial \delta_m}{\partial t} - \frac{\partial z_b}{\partial t}\right) \quad (k=1, 2, \dots, N)$$
(4)

where δ_m is the mixing layer thickness, which is related to bed material size or sand dune height; $\partial z_b / \partial t$ is the total bed deformation rate, $\partial z_b / \partial t = \sum_{k=1}^{N} (\partial z_b / \partial t)_k$; p_{bk}^* is p_{bk} when $\partial \delta_m / \partial t - \partial z_b / \partial t \le 0$, and p_{bk}^* is the percentage of size class k of bed material in the subsurface layer (below the mixing layer) when $\partial \delta_m / \partial t - \partial z_b / \partial t > 0$.

2.2 CCHE2D Model Equations

CCHE2D has two versions based on the Efficient Element Method (Jia and Wang, 1999; Wu, 2001) and Finite Volume Method (Wu, 2004). Both adopt the following 2-D shallow water equations:

$$\frac{\partial h}{\partial t} + \frac{\partial (hU)}{\partial x} + \frac{\partial (hV)}{\partial y} = 0$$

$$\frac{\partial (hU)}{\partial t} + \frac{\partial (hUU)}{\partial x} + \frac{\partial (hVU)}{\partial y} = -gh\frac{\partial z_s}{\partial x} + \frac{1}{\rho}\frac{\partial (hT_{xx})}{\partial x} + \frac{1}{\rho}\frac{\partial (hT_{xy})}{\partial y} + \frac{\partial D_{xx}}{\partial x} + \frac{\partial D_{xy}}{\partial y} + \frac{1}{\rho}(\tau_{sx} - \tau_{bx}) + f_chV$$
(6)

$$\frac{\partial(hV)}{\partial t} + \frac{\partial(hUV)}{\partial x} + \frac{\partial(hVV)}{\partial y} = -gh\frac{\partial z_s}{\partial y} + \frac{1}{\rho}\frac{\partial(hT_{yx})}{\partial x} + \frac{1}{\rho}\frac{\partial(hT_{yy})}{\partial y} + \frac{\partial D_{yy}}{\partial x} + \frac{\partial D_{yy}}{\partial y} + \frac{1}{\rho}(\tau_{sy} - \tau_{by}) - f_chU$$

$$(7)$$

where x and y are the horizontal Cartesian coordinates; h is the flow depth; U and V are the depthaveraged flow velocities in x- and y-directions; z_s is the water surface elevation; g is the gravitational acceleration; T_{xx} , T_{xy} , T_{yx} and T_{yy} are the depth-averaged turbulent stresses; D_{xx} , D_{xy} , D_{yx} and D_{yy} are the dispersion terms due to the nonuniformity of flow velocity and the effect of secondary flow, which are important in the situation of curved channels; ρ is the density of water; τ_{bx} and τ_{by} are the bed shear stresses, determined by $\tau_{bx} = \rho c_f U \sqrt{U^2 + V^2}$ and $\tau_{by} = \rho c_f V \sqrt{U^2 + V^2}$, with $c_f = gn^2/h^{1/3}$ and n is Manning's roughness coefficient; τ_{sx} and τ_{sy} represent the shear forces acting on the water surface, usually caused by wind driving; and f_c is the Coriolis coefficient.

CCHE2D models compute the total-load sediment using a single governing equation or separately calculate the bed-load and suspended-load transport using two equations. The latter approach is introduced here. The depth-averaged transport equation of suspended sediment is

$$\frac{\partial(hC_k)}{\partial t} + \frac{\partial(UhC_k)}{\partial x} + \frac{\partial(VhC_k)}{\partial y} = \frac{\partial}{\partial x} \left(\varepsilon_s h \frac{\partial C_k}{\partial x} \right) + \frac{\partial}{\partial y} \left(\varepsilon_s h \frac{\partial C_k}{\partial y} \right) + \frac{\partial S_x}{\partial x} + \frac{\partial S_y}{\partial y} + \alpha \omega_{sk} \left(C_{*k} - C_k \right)$$
(8)

where C_k is the depth-averaged suspended-load concentration; C_{*k} is the suspended-load transport capacity or the depth-averaged suspended-load concentration at the equilibrium state; ε_s is the turbulence diffusivity coefficient of sediment, determined with $\varepsilon_s = v_t / \sigma_c$, in which σ_c is the turbulent Schmidt number, usually having a value between 0.5 and 1.0 or determined by using van Rijn's (1989) method; ω_{sk} is the settling velocity of sediment; and α is the non-equilibrium adaptation coefficient.

In Eq. (8), S_x and S_y are the dispersion terms to account for the effect of the nonuniform distributions of flow velocity and sediment concentration. In the nearly straight (or slightly curved) channels with simple geometry, the dispersion terms are usually combined with the diffusion terms by adjusting the diffusivity coefficient (also called the mixing coefficient). In curved channels, due to the effect of helical motions, the dispersion terms become more important and are evaluated using the method proposed by Wu and Wang (2004a).

The bed-load transport is determined by

$$\frac{\partial(\delta_b \bar{c}_{bk})}{\partial t} + \frac{\partial(\alpha_{bx} q_{bk})}{\partial x} + \frac{\partial(\alpha_{by} q_{bk})}{\partial y} + \frac{1}{L_s} (q_{bk} - q_{b*k}) = 0 \quad (k=1, 2, ..., N)$$
(9)

where \bar{c}_{bk} is the average concentration of bed load at the bed-load zone; q_{bk} is the bed-load transport rate of size class k; q_{b*k} is the corresponding bed-load transport capacity or bed-load transport rate at the equilibrium state; and α_{bx} and α_{by} are the direction cosine components of bed-load movement, which is assumed to be along the direction of bed shear. In case of curved channels, α_{bx} and α_{by} are corrected to consider the effects of helical motions and channel slope (Wu and Wang, 2004a).

The bed deformation is calculated by

$$\left(1 - p'_{m} \left(\frac{\partial z_{b}}{\partial t}\right)_{k} = \alpha \omega_{sk} \left(C_{k} - C_{*k}\right) + \left(q_{bk} - q_{b*k}\right) / L_{s} \quad (k=1, 2, ..., N)$$
(10)

The suspended- and bed-load transport capacities C_{*k} and q_{b*k} are determined using empirical formulas described later. These formulas can be written in a general form similar to Eq. (3).

The variation of bed material gradation in the mixing layer in a depth-averaged 2-D model is determined by Eq. (4) at each computational node.

2.3 CCHE3D Model Equations

CCHE3D flow model solves either the full 3-D hydrodynamic equations (Reynolds equations) or the 3-D shallow water equations. In addition, the FAST3D model (Wu et al., 2000) is used by the first author as a research tool, and it solves the full 3-D hydrodynamic equations.

As shown in Fig. 1, the moving sediment is divided into suspended load and bed load and hence the flow domain is divided into a bed-load layer with a thickness of δ and the suspended-load layer above it with a thickness of $h - \delta$. The exchange of sediment between the two layers is through deposition (downward sediment flux) at a rate of D_b and entrainment from the bed-load layer (upward flux) at a rate of E_b . The distribution of the sediment concentration in the suspended-load layer layer is governed by the following convection-diffusion equation:

$$\frac{\partial c}{\partial t} + \frac{\partial \left[\left(u_j - \omega_s \delta_{j3} \right) c \right]}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\frac{v_t}{\sigma_c} \frac{\partial c}{\partial x_j} \right)$$
(11)

where *c* is the local concentration of suspended load; and δ_{j3} is the Kronecker delta with *j*=3 indicating the vertical direction.



Fig. 1 Configuration of Flow and Sediment Transport (Wu et al., 2000)

At the free surface, the vertical sediment flux is zero and hence the condition applied is

$$\frac{v_t}{\sigma_c}\frac{\partial c}{\partial z} + \omega_s c = 0 \tag{12}$$

At the lower boundary of the suspended sediment layer, the deposition rate is $D_b = \omega_s c_b$ while the entrainment rate E_b is

$$E_b = -\frac{V_t}{\sigma_c} \frac{\partial c}{\partial z} = \omega_s c_{b*}$$
(13)

where c_{b*} is the equilibrium concentration at the reference level $z = z_b + \delta$, which needs to be determined using an empirical relation.

In the 3-D model, the bed-load transport is simulated by using Eq. (9), with α_{bx} and α_{by} being the direction cosines of the bed shear stress known from the 3-D flow calculation. However, in case of steep slopes, the effect of gravity on the bed-load transport is taken into account through Wu's (2004) method.

The bed change can be determined by either the exchange equation

$$\left(1-p'_{m}\right)\frac{\partial z_{b}}{\partial t}=D_{b}-E_{b}+\frac{1}{L_{s}}\left(q_{b}-q_{b*}\right)$$
(14)

or the overall sediment mass-balance equation integrated over the water depth *h* (i.e. from $z = z_b$ to z_s).

3. MODEL CLOSURE AND AUXILIARY RELATIONS

3.1 Turbulence Model Closures

In general situations where the turbulence is approximately isotropic, CCHE2D and CCHE3D models use Boussinesq's assumption to determine the turbulent stresses, in which the eddy viscosity is given by the parabolic eddy viscosity model, the mixing length model, the standard k- ε turbulence model, the RNG k- ε turbulence model, etc. To capture the turbulence-generated flow features, CCHE3D adopts the non-linear k- ε turbulence model (Speziale, 1987) to determine the turbulent stresses instead.

3.2 Channel Roughness

In natural rivers, the banks and bed usually have different roughness. The bank roughness elements include bank materials, channel training works, hydraulic structures, vegetation, etc., while the bed roughness elements include rigid bed materials and movable bed forms such as sand ripples, sand dunes, alternate bars, islands, etc. NCCHE models use van Rijn's (1989) and Wu and Wang's (1999) methods to calculate the roughness on a movable bed. However, these empirical relations may give different predictions at different sites or times. For a site-specific study, NCCHE models often use the channel roughness calibrated with the available measurement data as an alternative. If highly accurate predictions of flow and sediment transport processes are required, the spatial and temporal distributions of the roughness are identified by the optimization scheme proposed by Ding et al. (2004).

Following Shimizu and Tsujimoto (1994) and Lopez and Garcia (2001), CCHE2D and CCHE3D models have been implemented an alternative to account for the effect of vegetation roughness by considering the drag force interaction between fluid and vegetation in the momentum equations and the turbulence generated by vegetation in the k and ε equations. After the effect of vegetation on the flow is considered, its effect on sediment transport and channel morphology change can also be simulated (Wu et al., 2005).

3.3 Non-equilibrium Adaptation Length

The non-equilibrium adaptation length L_s , which characterizes the distance for sediment to adjust from a non-equilibrium state to an equilibrium state, is a very important parameter in the non-equilibrium transport approach used in NCCHE models. For suspended load, $L_s = Uh/(\alpha \omega_{sk})$. The

coefficient α is calculated with Armanini and di Silvio's (1988) method. Values of α calculated from this method or other similar methods in the literature are usually larger than 1. However, in practice, α has been given different values by many researchers, most of them being less than 1. Based on results obtained from validation tests in many reservoirs and rivers, it has been suggested that α =1 for the case of strong erosion, α =0.25 for strong deposition, and α =0.5 for weak erosion and deposition in 1-D model (Han, 1980; Wu et al., 2004).

For bed load, the non-equilibrium adaptation length is related to the dimensions of sediment movements, bed forms, and channel geometry. Wu et al. (2004) suggested that it takes the value of the length of the dominant bed forms, such as sand dunes in laboratory cases and alternate bars in field cases. This suggestion has given very promising results in a series of applications.

For bed-material load, the non-equilibrium adaptation length is set as the larger of the adaptation lengths computed for bed load and suspended load. For wash load, the adaptation length L_s is assumed to be infinitely long and then no sediment exchange exists near the bed.

3.4 Non-cohesive Sediment Transport Formulas

The nonuniform sediment transport capacity is determined using Wu, Wang and Jia's formula (2000), the modified Ackers and White's (1973) formula (Proffit and Sutherland, 1983), modified Engelund and Hansen Formula (Wu and Vieira, 2002), SEDTRA module (Garbrecht et al., 1995) in CCHE1D and CCHE2D models. All these formulas have considered the hiding and exposure mechanism in nonuniform sediment transport. Ribberink et al. (2002) and Wu and Wang (2003) found that Wu, Wang and Jia's (2000) formula performs best among the tested formulas. The equilibrium near-bed concentration of suspended load in CCHE3D model is determined using the method proposed by van Rijn (1989).

3.5 Cohesive Sediment Transport Formulas

CCHE2D model simulates the cohesive sediment transport with special consideration of flocculation, settling, transport, erosion, deposition and consolidation processes. The transport of cohesive sediment is treated as suspended load and governed by Eq. (8). The size of flocs and in turn the settling velocity is related to the particle size, sediment concentration, salinity, and turbulence intensity. The settling velocity of the flocs is determined by (Wu and Wang, 2004b)

$$\frac{\omega_f}{\omega_{d50}} = K_d K_s K_{sa} K_t \tag{15}$$

where ω_f is the representative settling velocity of the flocs; ω_{d50} is the settling velocity of single particles corresponding to the median size d_{50} of the sediment mixture; K_d , K_s , K_{sa} and K_t are the correction factors accounting for the influences of sediment size, sediment concentration, salinity, and turbulence intensity, respectively.

The erosion rate is determined using Partheniades' (1965) linear relation or Gailani et al.'s (1991) power function. The deposition rate is calculated using Mehta and Partheniades' (1975) formula. The decrease in bed elevation due to the consolidation is determined by

$$\frac{dH}{dt} = -\frac{H}{\overline{\rho}_d} \frac{d\rho_d}{dt}$$
(16)

where *H* is the thickness of the deposited cohesive sediment; and $\overline{\rho}_d$ is the mean dry density of the deposit.

3.6 Local Scour near In-stream Structures

The three-dimensional flow features, such as the downward flow, horseshoe and wake vortices, and the localized pressure gradient, are all important in the development of local scour near in-stream structures. Considering the effects of these three-dimensional flow features, Dou (1997), Jia et al. (2001), and Wu and Wang (2004c) have attempted to extend the capability of general sediment transport formulas to the local scour simulation near bridge piers, abutments and spur-dykes as well as the headcut.

3.7 Sediment Transport on Steep Slopes

For the channels with steep slopes, the effect of the gravity on sediment transport is an important factor. Two approaches have been applied to consider this effect in the sediment transport capacity function in the form of $q_{b*} = f(\tau_b/\tau_c)$, where τ_b is the bed shear stress and τ_c is the critical shear stress for the incipient motion of bed material. One is to correct the critical shear stress τ_c using the method of Brooks (1963) or van Rijn (1989). This approach has been used to modify such as van Rijn's (1989) formula. The other is to add the streamwise component of the gravitational force to the bed shear τ_b without modifying τ_c (Wu, 2004)

$$\tau_{be} = \tau_b + \lambda_0 \tau_c \sin \varphi / \sin \phi \tag{17}$$

where τ_{be} is the effective tractive force; φ is the bed angle with the horizontal, with positive values denoting downslope bed; ϕ is the repose angle; and λ_0 is a coefficient related to flow and sediment conditions as well as the bed slope (Wu, 2004). Eq. (17) has been used to modify Wu, Wang and Jia's (2000) formula,

The gravity also affects the direction of bed-load transport. As suggested by Wu (2004), the parameters α_{bx} and α_{by} in Eq. (9) are replaced by $\alpha_{bx,e}$ and $\alpha_{by,e}$ that are determined as

$$\frac{\alpha_{bx,e}}{\alpha_{by,e}} = \frac{\alpha_{bx}\tau_b + \lambda_0 \tau_c \sin \varphi_x / \sin \phi}{\alpha_{by}\tau_b + \lambda_0 \tau_c \sin \varphi_y / \sin \phi}$$
(18)

where φ_x and φ_y are the bed angles along x- and y-directions.

3.8 Effect of Helical Flow Motions on Sediment Transport in Curved Bends

Helical (secondary) motions in curved channels play an important role in the evolution of channel morphology, inducing deposition along the inner bank and erosion along the outer bank. This phenomenon can be simulated by the CCHE3D model and FAST3D model (Wu et al., 2000). However, for saving computing time, following Flokstra (1977), Wu and Wang (2004a) have modified the CCHE2D model to include the effect of the helical motions. The dispersion terms in Eqs. (6)-(8) are determined by the linear model that uses the following algebraic equation for the vertical distribution of the helical flow velocity

$$u_n = U_n + b_s I\left(\frac{2z}{h} - 1\right),\tag{19}$$

the logarithmic or power distribution for the stream-wise flow velocity, and the Rouse distribution or Lane-Kalinske distribution for the suspended-load concentration along the depth. In Eq. (19), u_n is the local velocity in the cross-stream direction; b_s is the coefficient with a value of about 6.0; U_n is the depth-averaged velocity in the cross-stream direction; I is the intensity of helical motions. Theoretically, $I = U_s h/r$ in the channel centerline (Rozovskii, 1957). Here, r is the local radius of curvature. For the entire channel bend, de Vriend (1981) proposed a differential transport equation to determine the intensity I. Wu and Wang (2004a) simplified this differential equation into an algebraic formula for the helical flow intensity in the fully developed region. In addition, the methods proposed by Engelund (1974) and Odgaard (1981) are used to account for the effect of the helical flow on the bed-load transport direction.

3.9 Bank Erosion and Mass Failure

Bank erosion is the main cause of channel widening and meandering. To realistically model the morphological evolution of channels with movable banks, both bed and bank changes should be simulated (Duan et al., 2001; Wu and Vieira, 2002). For non-cohesive banks, bank collapses when the slope angle is larger than the repose angle. Thus the retreat of non-cohesive banks is simulated by imposing the repose angle in NCCHE models. For cohesive banks, the lateral fluvial erosion at bank toes is calculated using Arulanandan et al.'s (1980) empirical relationship, and bank mass failure is simulated using Osman and Thorne's (1988) algorithm.

3.10 Integration of Channel and Watershed Models



Fig. 2 Integration of Channel and Watershed Models

CCHE1D has been designed for integration with the watershed model AGNPS (and SWAT) (Wu and Vieira, 2002). This integrated modeling system includes three components: landscape analysis, watershed modeling, and channel simulation, as shown Fig. 2. The landscape analysis program TOPAZ is used to extract the channel network and the corresponding subcatchments based on the elevation data from a Digital Elevation Model. The watershed model computes daily runoff and

sediment yield for each subcatchment. The channel model simulates the flow and sediment transport in the channel network using the boundary conditions provided by the watershed model.

4. NUMERICAL METHODS

The NCCHE sediment transport models are solved by very efficient numerical schemes based on the efficient element method (EEM), finite difference method (FDM), and finite volume method (FVM). CCHE1D adopts the traditional Preissmann's implicit scheme for the common flows in natural rivers and the newly-developed Ying et al.'s (2003) explicit scheme for dam-break type flows. CCHE2D and CCHE3D models adopt the fully implicit schemes for the temporal derivative terms, and discretize the convection terms using upwind schemes, such as hybrid upwind/central difference scheme, exponential difference scheme, the upwind interpolation scheme (Wang and Hu, 1992), QUICK scheme, HLPA scheme, and SOUCUP scheme (Zhu, 1992). The latter two schemes are of second-order accuracy and without numerical oscillations. The sediment transport models are driven by flow simulation engines that adopt many advanced computation techniques with high efficiency, such as the projection method and SIMPLEC algorithm for 2-D and 3-D hydrodynamic models. The 2-D and 3-D discretized governing equations are solved by using Strongly Implicit Procedure (SIP), and the 1-D equations are by the Thomas algorithm. These solvers have fast convergence.

In addition, a semi-coupling procedure is used in NCCHE models, in which the flow and sediment calculations are decoupled but the sediment transport, bed change and bed material sorting calculations are coupled in the sediment modules, as shown in Fig. 3. This semi-coupling procedure has been found to be very stable and efficient computationally.



Fig. 3 Semi-Coupling Procedure for Flow and Sediment Calculations

5. MODEL VERIFICATIONS AND APPLICATIONS

All NCCHE sediment transport models have been verified and validated comprehensively using analytic solutions, laboratory experiments, and field measurements, following the procedure suggested by the ASCE Task Committee on 3D Free Surface Flow Model Verification and Validation (Wang, 2005). After well verified, NCCHE models have been widely applied to a variety of cases with success. A few examples are given below.

Case 1: Integrated Watershed-Channel Simulation in Goodwin Creek

The Goodwin Creek watershed in Mississippi is an experimental watershed in the USA, which has been monitored continuously since 1978. Fig. 4(left) shows the comparison of the calculated and measured thalweg changes of the main channel from 1978 to 1992. Fig. 4(right) shows the comparison of the calculated and measured annual sediment yields at the watershed outlet. The reasonable agreement proves that computational model, CCHE1D, is capable of simulating long-term morphological changes of a stream.



Fig. 4 Sediment Transport in the Goodwin Creek Watershed: (left) Thalweg Changes; (right) Sediment Yields at Outlet

Case 2: Vegetation Effect on Fluvial Processes in Little Topashaw Creek

The FVM-based CCHE2D model has been used to investigate the effect of the manmade large woody debris structures on the fluvial processes in the Little Topashaw Creek, Mississippi (Wu et al., 2005). Fig. 5(left) shows the photo of the study site, and Fig. 5(right) shows the simulated bed change during 2001-2002 after the structures were constructed. One can see that sediment deposition occurred along the outer bank where the structures located, while erosion occurred in the main channel. The simulated results are in reasonably good agreement with measurement data.



Fig. 5 Large Woody Debris Structures in the Little Topashaw Creek: (left) Photo facing upstream; and (right) Simulated Bed Change

Case 3: Cohesive Sediment Transport in Gironde Estuary

The FVM-based CCHE2D model was applied to simulate the tidal flow and cohesive sediment transport in the Gironde Estuary, France. To account for the effect of salinity on cohesive sediment

transport, the salinity transport was also computed. Fig. 6 shows the comparison of the simulated and measured tidal levels, salinities, and sediment discharges in May 19-22, 1974. The simulation results agree well with the measurement.



Fig. 6 Tidal Flow, Sediment and Salinity Transport in Girond Estuary

6. CONCLUSIONS

Sediment transport modeling has been advanced significantly over the past two decades in NCCHE. The three-dimensional models can simulate the detailed flow characteristics of complex situation, e.g. the turbulent flow in a highly irregular river bendway with spur dikes and submerged weirs, the local scour development in time around bridge piers and abutments, etc. The two-dimensional models have been successfully applied to the predictions of flood flows due to over topping of river banks, dam break or levee breach caused by heavy rain storms, the selection of designs for river restoration projects by a variety of techniques including the utilization of vegetations and hydraulic structures in stream or along the banks, etc. The one-dimensional models are being used in assessing long-term sediment and/or pollutant transport in streams and channel networks, predicting the total maximum daily loads in a catchment or watershed, evaluating the effectiveness of erosion control structures from long-term point of view, and many other cases. These models are becoming the predictive tools in decision support systems, which are to have wider and wider applications in policy making, management planning and engineering designs to select the best management practices and the optimal design to satisfy all constraints of environment, ecology, political/legal systems, social/cultural concerns, etc. There is no doubt that NCCHE's sediment transport models are to be more and more widely adopted by engineers and practitioners.

NCCHE sediment transport models will be continuously improved and upgraded using the newly proved sediment transport theories, the newly found empirical functions, the newly developed numerical solution methods, the newly collected laboratory and field measurement data, the newly developed information technologies, etc. Furthermore, the sediment transport models will be integrated in greater extents with the other models, such as ecosystem model, water quality model, pollutant transport model, even economic, management, social systems models, etc. for better analysis and solution of the global or regional problems encountered in real-life engineering.

ACKNOWLEDGEMENTS

This study is part of the research project sponsored by the USDA-ARS Specific Research Agreement No.58-6408-2-0062 (monitored by the USDA-ARS National Sedimentation Laboratory) and the University of Mississippi.

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