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A graded sediment transport and bed evolution model in estuarine basins and its application to the Yellow River Delta

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Abstract

Details are given in present paper of the development of a sediment transport and morphological model to predict the bed evolution processes in tidal flows. The model is based on an existing hydrodynamic and sediment transport model (DIVAST-SED), but with significant refinements being made. A single size sediment transport module is refined to include capability for simulating the transport of graded sediments under non-equilibrium conditions. Both cohesive sediment and non-cohesive sediment are taken into consideration in present study. The fall velocity of suspended sediment is modified in present model due to the high sediment concentration. A 3-layer approach is adopted to simulate the variations of sediment gradations of bed materials.

The model is used to simulate the bed evolution in the Yellow River Delta from 1992 to 1995, the numerical results show how the morphology developed in the Yellow River Delta and agree well with the field data. The present model could provide an effective tool for the management of wetland in the Yellow River Delta.

Keywords: bed evolution, graded sediments，morphology, sediment transport, Yellow River Delta

1. Introduction

The bed evolution process in estuarine and coastal basins has been extensively investigated both experimentally and numerically in the past decades. In estuarine, the river may takes large quantity of sediment to the river mouth discontinuously and the water level rises and falls regularly driven by the tide. The common features of these water bodies are that they normally have a shallow water depth, a complicated geometry and a high biochemical activity. The interaction between the fluid flows, sediment transport and bed level changes has great importance to some other water environmental issues and river mouth wetland functions.

Schramkowski et al [14] analysed the effects of geometry and bottom friction on local bed forms in a tidal embayment. In their study the water motion was modelled using the depth-averaged shallow water equations and

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driven by an externally prescribed M2 tide, with the transport of suspended load being considered. Van Rijn et al [20] built a numerical model using a software package, namely DELFT3D, to simulate the bed evolution at an artificial sand ridge near Hoek van Holland, located close to the harbour of Rotterdam in the Netherland. In this study, the mean sediment size was about 0.3 mm. A one dimensional depth-averaged (1DH) model, a two-dimensional vertical (2DV) model and a three-dimensional (3D) model were separately used. The results show that the sand ridge grows when the bed load transport is dominant, while the ridge recedes when the suspended load transport is dominant. Chung and Eppel [4] investigated the sensitivity of sediment transport and bed morphology with respect to the bed slope and grain size, and the non-hydrostatic pressure term through numerical simulations based on a 3D hydrodynamic and sediment transport model.

In estuarine and coastal basins, the sediments are usually highly graded, ranking from very fine to rather coarse particles. Although many efforts have already been made, existing methods are sometimes still inadequate when used for estimating the non-uniform sediment transport under non-equilibrium conditions. The pioneering research to fractionally calculate the graded bed load transport rate was attributed to Einstein [5]. Based on the theories of bed load transport of non-uniform sediment Ashida and Michiue [1] proposed an analytical model to predict the grain size frequency distribution of armour coat and the amount of river bed degradation. They used the model to determine the degradation of a river bed composed of graded material downstream of a dam. Parker et al. [13] used field data to study the size distribution of bed load sediment in paved gravel-bed streams. Misri et al. [12] proposed a conceptual model to predict the effects of a particular size of sediment fraction on the transport rates of other sediment size fractions. They also used some experimental data to study the accuracy of several existing methods for computing the bed load transport rate. Bridge and Bennett [2] developed a model for estimating the entrainment and bed load transport of sediment grains of different sizes, shapes and densities by a unidirectional turbulent flow, with the behavior of the model being explored extensively by comparing predictions with data acquired from flumes and rivers. Wu et al [24] developed a correction factor to account for the hiding and exposure mechanism of non-uniform sediment transport and derived formulations to calculate the critical shear stress of incipient motion and the fractional bed load and suspended load transport rates of non-uniform sediment.

In the present study a two-dimensional depth-integrated numerical model has been refined based on DIVAST model to predict the hydrodynamic, sediment transport and morphological processes in estuarine basins. The existing DIVAST model can simulate the hydrodynamic characteristics in estuarine basins well and has been verified with many data sets obtained from laboratory and field studies [7] [9]. In the refined model, a single size sediment transport model has been refined to a multiple-fractions transport model. Each fraction of sediment is simulated separately, assuming that the size fractions don't influence each other's movement. The evolution of the bed is the result of erosion or sedimentation. In order to account for the influence of bed sediment composition on the overall transport process, a method of multiple bed layers is used to represent the spatial and temporal variations of sediment gradations of the loose bed layers. Considering the high sediment concentration of Yellow River, the fall velocity of suspended sediment is modified in present model according to practical sediment concentration.

The model is finally used to simulate the bed evolution in Yellow River Delta (YRD), the YRD is located in the connection zone of Yellow River and Bohai Sea, which is the base of energy sources, petroleum and agriculture of Shandong Province of China. The most active land-ocean interaction in the world takes places in this area because of the river flow with the highest sediment concentration and the sea with the typical weak-tide character, which makes the topography of YRD change intensely all the time. The present model is used to simulate the bed evolution in the YRD from 1992 to 1995, the numerical predictions by the present model are compared with experimental measurements and the predictions based on a single size model.

2. Numerical model details

2.1 Governing equations for hydrodynamic process

The hydrodynamic model used to predict the water elevation and velocity fields in coastal, estuarine and riverine waters involves the solution of the governing equations of fluid flow. The two-dimensional hydrodynamic equations are generally based on the depth-integrated 3-D Reynolds equations for incompressible and unsteady turbulent flows, with the effects of the earth's rotation, bottom friction and wind shear being included. A useful feature of the model for the present study is its capacity in dealing with the flooding and drying processes [6]. More details of the governing hydrodynamic equations and solution methods can be found in Falconer [7].

2.2 Governing equations for sediment transport process

In estuarine and coastal waters, the sediments are usually highly graded, ranking from very fine to rather coarse particles. The transport properties of such sediments may vary significantly. Thus in some situations it is problematic by using a single diameter to represent all of the sediments. In the present study, the graded sediment is divided into *N* fractions according to the particle size distribution.

It is widely accepted that the suspended sediment concentration can be described by the advective-diffusion equation. For horizontal or quasi-horizontal flows, the 3D solute mass balance equation can be integrated over the water depth to obtain the 2D depth-integrated advective-diffusion equation, giving

$$\frac{\partial H\phi_i}{\partial t}+\frac{\partial HU\phi_i}{\partial x}+\frac{\partial HV\phi_i}{\partial y}=\frac{\partial}{\partial x}\left[D_{xx}H\frac{\partial\phi_i}{\partial x}+D_{xy}H\frac{\partial\phi_i}{\partial y}\right]+\frac{\partial}{\partial y}\left[D_{yx}H\frac{\partial\phi_i}{\partial x}+D_{yy}H\frac{\partial\phi_i}{\partial y}\right]+HS_{si} \tag{1}$$

where ϕ_i = depth averaged suspended sediment concentration for the *i*th (*i=1,2…N*) fraction, D_{xx}, D_{yx}, D_{yx}, D_{yy} = depth averaged diffusion coefficients in the *x* and *y* direction [9]. S_{si} is a source term for the *i*th fraction which represents the erosion and deposition fluxes.

In coastal and estuarine waters the water, depth *H* may vary rapidly, thus the monotonicity of the depth integrated concentration ($\phi_i H$) may be different from the monotonicity of the solute concentration (ϕ_i). In order to achieve high accuracy and mass conservation, Wu and Falconer [23] rearranged equation (1), with an additional source term being introduced into the two-dimensional depth integrated advective-diffusion equation. In the current study, this modification is included in the sediment transport equation, i.e.

$$\frac{\partial\phi_i}{\partial t}+\frac{\partial U\phi_i}{\partial x}+\frac{\partial V\phi_i}{\partial y}=\frac{1}{H}\frac{\partial}{\partial x}\left[D_{xx}H\frac{\partial\phi_i}{\partial x}+D_{xy}H\frac{\partial\phi_i}{\partial y}\right]+\frac{1}{H}\frac{\partial}{\partial y}\left[D_{yx}H\frac{\partial\phi_i}{\partial x}+D_{yy}H\frac{\partial\phi_i}{\partial y}\right]+S_{si}+S_{ai} \tag{2}$$

where S_{ai} = the additional source term for the *i*th fraction, which can be calculated as:

$$S_{ai}=\phi_i\left(\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}\right) \tag{3}$$

The additional source term has shown to be vital for mass conservation in modelling mass and solute transport.

For cohesive sediment (diameter <0.063mm), S_{si} in equation (2) can be calculated by

$$S_{si}=(E-D)/H \tag{4}$$

where *E* is erosion flux and *D* is the depositional flux which could be found in Winterwerp and van Kesteren [22].

For non-cohesive sediment, S_{si} can be calculated using [10]:

$$S_{si}=w_{si}(\phi_{aei}-\phi_{ai})/H \tag{5}$$

where ϕ_{ai} = sediment concentration for the ith fraction at a reference level "a" near the bed, and ϕ_{aei} = equilibrium sediment concentration for size fraction i at the reference level, w_{si} is the fall velocity of non-cohesive sediment, which can be calculated by van Rijn [19], but the fall velocity is strongly reduced when the sediment concentration are larger than 10000mg/l, which is called hindered settling. These effects are incorporated in the following relationship for the settling velocity [16] [19]:

$$w'_{si} = w_{si}(1-\frac{\phi_i}{\rho_s})^n \quad (6)$$

where ρ_s = sediment density, n = a coefficient for normal flow condition which is about 4 [19].
For equilibrium suspended sediment fluxes, then $\phi_{ai} = \phi_{aei}$ and S_{si} = 0. According to van Rijn ([18], see Figure 3) the reference level "a" is equal to the equivalent roughness height k_s with a minimum value being $a = 0.01H$.

The expression used in this study to define ϕ_{aei} follows from van Rijn [17] and it is written as:

$$\phi_{aei} = 0.015\frac{D_{50i}}{a}\frac{T_i^{1.5}}{D_{*i}^{0.3}}p_{ui} \quad (7)$$

where D_{50i} = median grain size for the ith fraction, p_{ui} = percentage of the ith fraction in the loose layer of bed, D_{*i} = dimensionless particle size parameter and T_i = transport stage parameter for the ith fraction.

In a depth-integrated 2-D model only the mean sediment concentration ϕ_i is available. Hence the value of the reference concentration ϕ_{ai} must therefore be related to the depth mean concentration ϕ_i, with this relationship being assumed to be of the following form [10]:

$$\frac{\phi_{ai}}{\phi_i} = \frac{\phi_{aei}}{\phi_{ei}} \quad (8)$$

where ϕ_{ei} = depth mean equilibrium concentration. Combining Equations (5) and (8) gives rise to the following net erosion or deposition rate: -

$$S_{si} = w_{si}\gamma(\phi_{ei} - \phi_i)/H \quad (9)$$

where $\gamma = \frac{\phi_{aei}}{\phi_{ei}}$.

The depth mean equilibrium concentration ϕ_{ei} can now be calculated from the ratio of the depth integrated equilibrium suspended sediment flux q_{si} and depth integrated fluid flux q_i, giving:

$$\phi_{ei} = \alpha\frac{q_{si}}{q_i} \quad (10)$$

in which α = a profile factor, assumed to be 1.13 after Celik and Rodi [3].

2.3 Bed level change

For each fraction, the corresponding bed elevation change can be determined by:

$$\frac{\Delta z_{bi}}{\Delta t}-\frac{1}{1-p_0}\gamma\omega_i(\phi_i-\phi_{ei})=0 \tag{11}$$

where p_0 = porosity of bed layer sediment. Within a time step, the total variation of bed level Δz_b is obtained using

$$\Delta z_b=\sum_{i=1}^{N}\Delta z_{bi}$$

2.4 Bed sediment size variation

The deformation of bed, especially the degrading process, is dominantly controlled by the composition of bed material. The scoured bed usually tends to be armoured to prevent further erosion, or to be fined for the case of deposition. To account for the influence of bed sediment composition, numerical models have been developed to solve the spatial and temporal variations of sediment gradation of the loose bed layers. This can be approached by dividing the loose sediment bed into several vertical layers. The present model adopts a 3-layers method proposed by Wei [21]. As shown in Figure 1, the loose bed is divided into the top, middle and bottom layers, with the thickness and volumetric fractions of these layers being defined as H_T, H_M, H_L and P_{Bi}, P_{Mi}, P_{Li} respectively. The superscript 0 indicates the initial values.

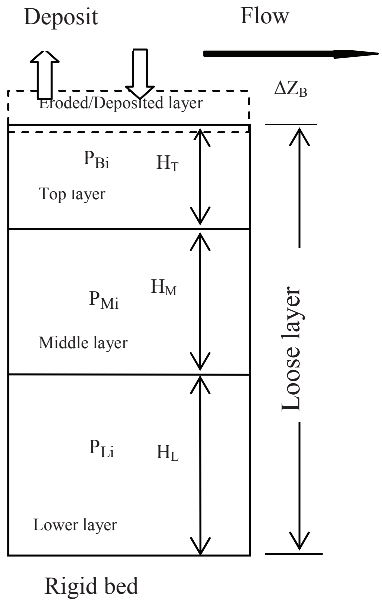

Figure 1 Bed sediment layers

Due to erosion or deposition, the fraction percentage of the top layer $H_T+\Delta Z_b$ during a small time interval can be computed using:

$$P_{ui} = \frac{H_T P_{Bi}^0 + \Delta Z_{Bi}}{H_T + \Delta Z_B} \tag{12}$$

where ΔZ_{Bi} = scoured or deposited thickness of an individual sediment fraction.

For the case of deposition, i.e. $\Delta Z_B > 0$, the fraction percentage of the top layer is calculated by (12). The fraction percentage of the middle layer can be calculated using:

$$P_{Mi} = \begin{cases} P_{ui} & \Delta Z_B \geq H_T \\ \dfrac{\Delta Z_B P_{ui} + (H_T - \Delta Z_B) P_{Mi}}{H_M} & \Delta Z_B < H_T \end{cases} \tag{13}$$

The fraction percentage of the bottom layer can be calculated using:

$$P_{Mi} = \begin{cases} \dfrac{(\Delta Z_B - H_M) P_{ui} + H_M P_{Mi}^0 + H_L^0 P_{Li}^0}{H_L^0 + \Delta Z_B} & \Delta Z_B \geq H_T \\ \dfrac{\Delta Z_B P_{Mi}^0 + H_L^0 P_{Li}^0}{H_L^0 + \Delta Z_B} & \Delta Z_B < H_T \end{cases} \tag{14}$$

On the other hand, for the case of erosion, i.e. $\Delta Z_B < 0$, the position of the top layer should be adjusted. The adjusted fraction percentage of the top layer can be calculated using:

$$P_{Bi} = \frac{(H_T + \Delta Z_B) P_{ui} - \Delta Z_B P_{Mi}^0}{H_T} \tag{15}$$

The fraction percentage of the middle layer can be calculated using:

$$P_{Bi} = \frac{(H_M + \Delta Z_B) P_{Mi}^0 - \Delta Z_B P_{Li}^0}{H_M} \tag{16}$$

The fraction percentage of the bottom layer doesn't change, but the thickness of the lower layer is adjusted according to:

$$H_L = H_L^0 + \Delta Z_B \tag{17}$$

The method is not restricted to only 3 layers. In order to increase model accuracy, the number of layers can be increased.

3. Numerical model application

The Yellow River has the highest sediment concentration in the world, which takes nearly 1 billion tons of sediment to the YRD and Bohai Sea every year [11]. Because of the weak-tide character of Bohai Bay, the tide current only can take 1/3 of sediment into the outer sea, so most of the sediments stay at the river mouth and make the topography of the YRD changes intensely all the time. In 1992, the YRD is located between 37°35'N and 37°40'N, 119°15'E and 119°20'E, as shown in Figure 2. The computational domain is divided by 567×495 square grids with a side length of 200m. The upstream boundary is located at Lijin station, Station X is 4.20km downstream from Lijin station along the river way, from the upstream to the Mouth into the Bohai Sea is about 86km long, The Qing VII and Qing VIII are two cross sections near the Mouth. There are several gullies on the bay of Bohai Sea.

Qingshui Gully was the tail channel of the Yellow River from 1976 to 1996, Shenxian Gully and Diaogou Gully were on the north shore. At Lijin station the bed elevation was found to be 12 m above the sea level while out of the Mouth the lowest bed elevation was approximately 18m below the sea level. The sediments of YRD in 1992 were subdivided into 6 fractions, with the average diameters and the corresponding percentage being listed in Table 1. Initially, the bed sediments were assumed to be homogenously laid on the bed, fractions 1-4 are considered as cohesive sediment while fractions 5 and 6 are regarded as non-cohesive sediment.

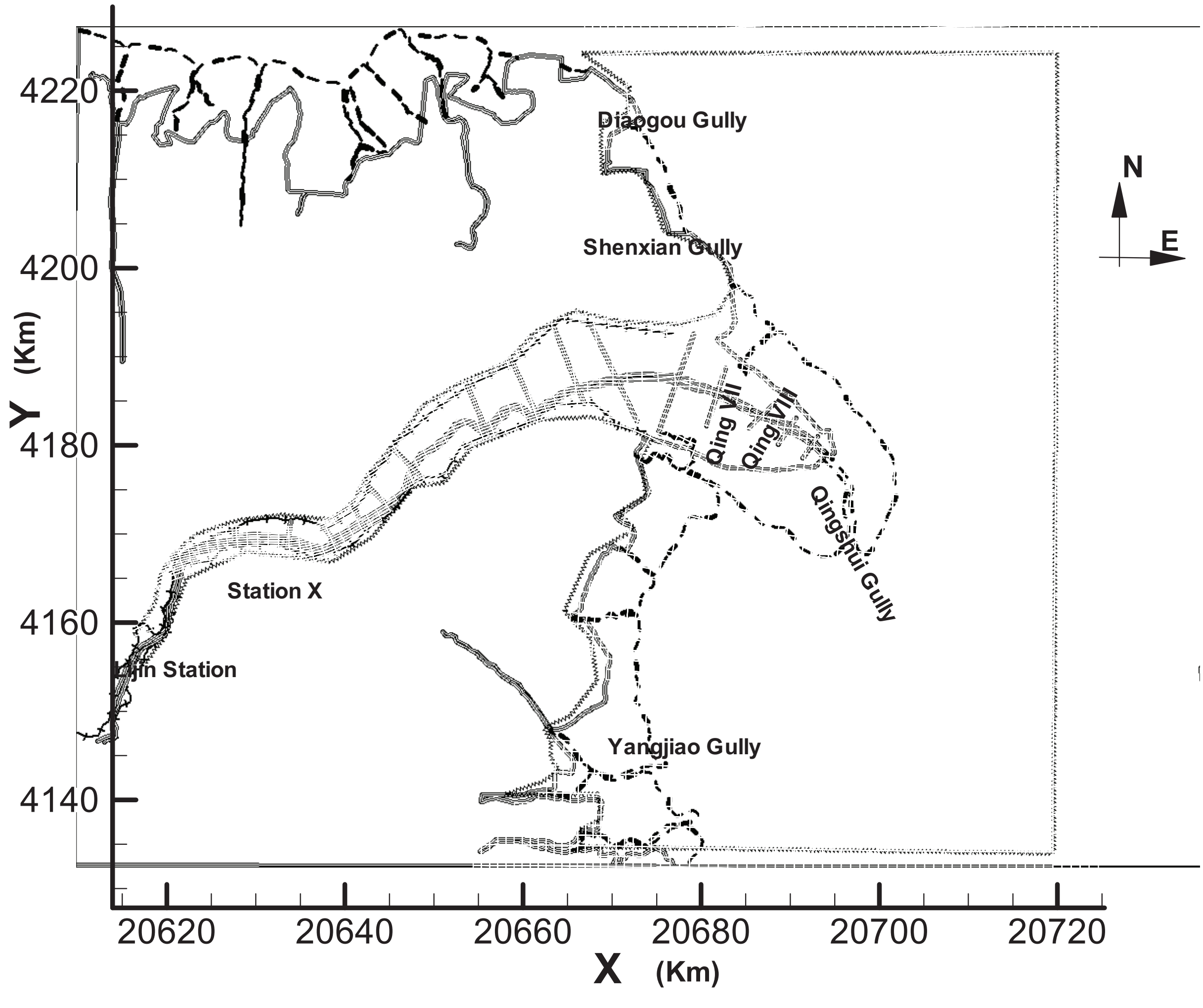

Figure 2 Location of Yellow River Estuary

Table 1 Fractional average sediment diameters and corresponding percentages

Fraction No	1	2	3	4	5	6
Diameter (mm)	0.0035	0.0085	0.0175	0.0375	0.075	0.175
%	22.6	5.5	19.3	25.5	25.3	1.8

The simulation started in January 1992 and ended in December 1995 before the artificial diversion. The time step is 20s and the total computational time for each run was about 24 hours using a 2.4 GH PC. The simulations considered the open boundary tidal elevations, surface wind stresses and high sediment concentration inflows. The upstream inflow boundary condition is a time series of flux at Lijin station as Figure 3 shown. Figure 4 shows the sediment concentration at Lijin station from 1992 to 2000. Three seawards open boundaries are set in the model as Figure 2 shown; the nonharmony constants of each tide boundary are obtained considering seven largest constituents including M2, S2, N2, K1, O1, M4 and M6. The salinity out of the Mouth in Bohai Sea is around 30.4.

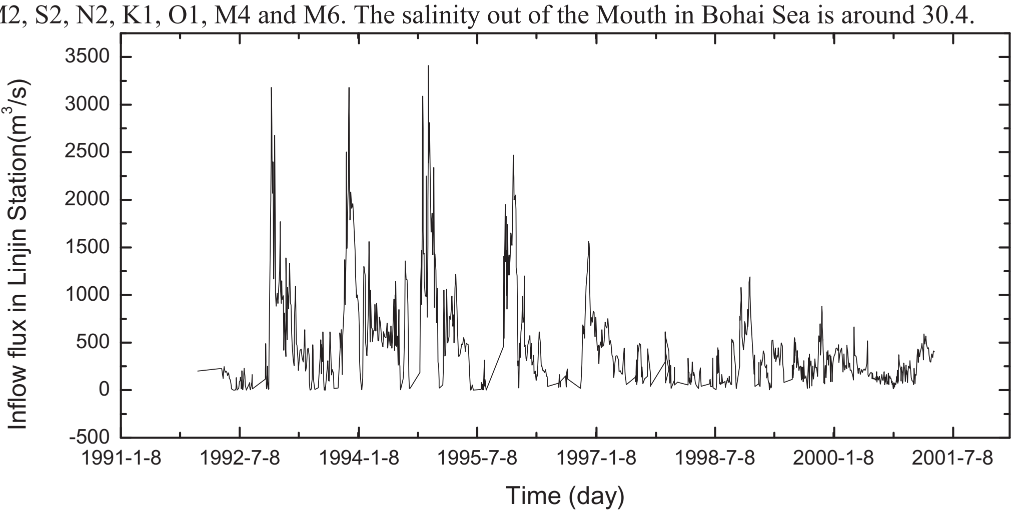

Figure 3 Inflow flux at Lijin station from 1992 to 2000

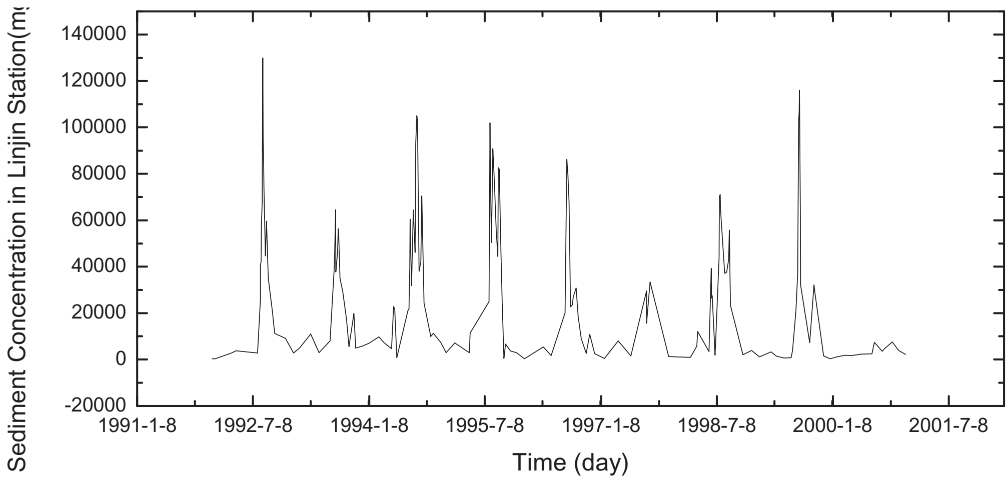

Figure 4 Sediment concentration at Lijin Station from 1992 to 2000

Figure 5 compares the measured and numerical tidal elevation in Shenxian Gully in a period，the measured tidal elevation in Shenxian Gully is Shi's paper [15] is plotted in the dash line, and the numerical data by present model is plotted in the solid line.

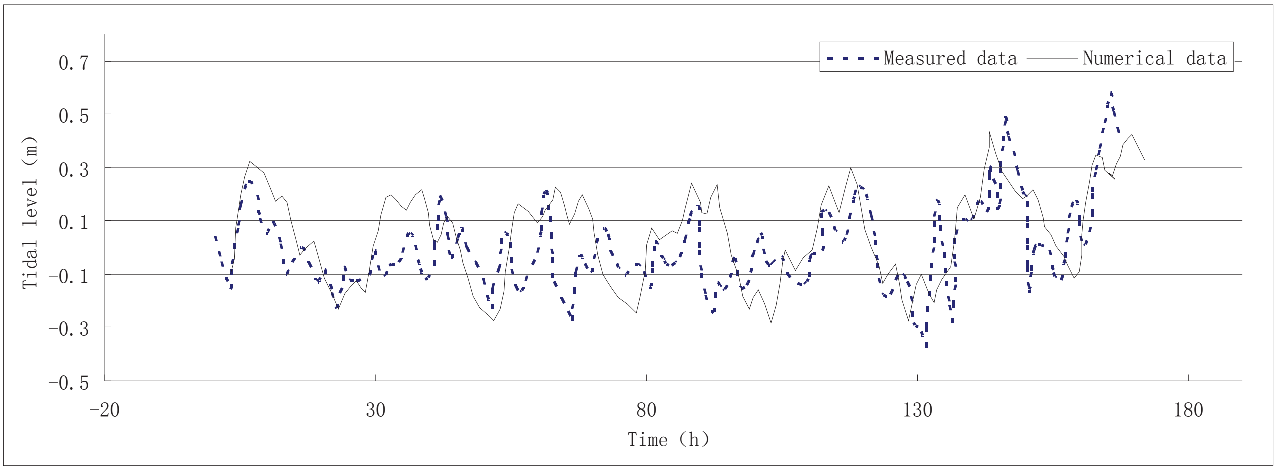

Figure 5 Tidal elevation in a period at Shenxian Gully

Figure 6 displays the sediment concentration from January 1992 to January 1996 in Shenxian Gully, the dash line is the measured data ranging from 350 to 140000 mg/l, and the solid line is the numerical data whose trend is mainly consistent with the measured data. The sediment concentration is extremely high in the summer time, nearly 140g/l, the peak values simulated are also in good agreement with the measurement.

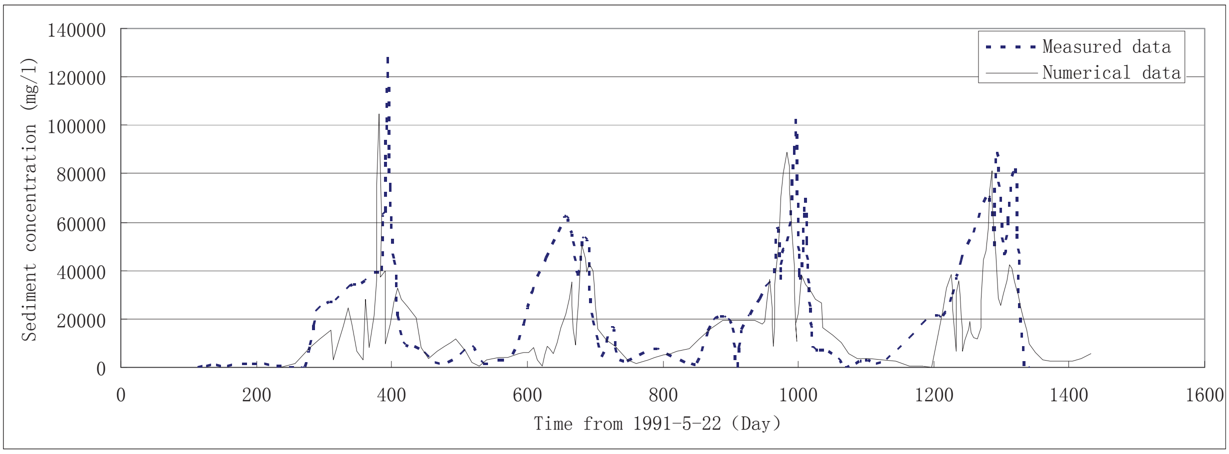

Figure 6 Sediment concentration at Shenxian Gully from 1991-5-22

Figure 7 shows the water surface level of the Station X from July 1992 to January 1994, the numerical water surface basically matches the measured data except a delay of fall after the peak arrives, that is mainly because a lot of flood plains come into being when water level increased, the newly-formed wet cells need to be eliminated from the computational domain after the peak passed away, the drying-wetting process adopted by present model need some time to do this job.

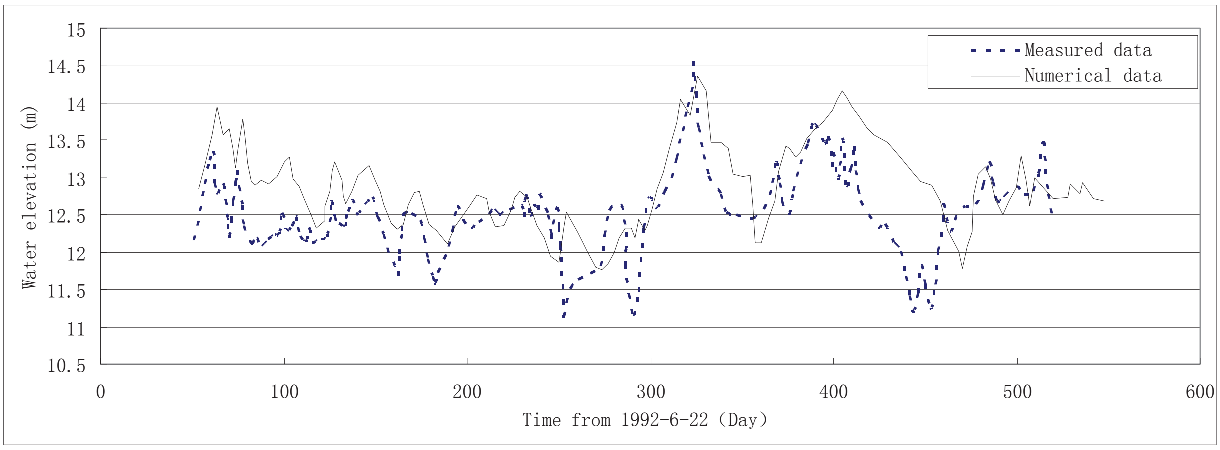

Figure 7 Daily water elevation from 1992-6-22 at station X

Figure 5-7 show that the present dynamic computation is correct and boundary condition is reasonable, which is fundamentally important for the longtime bed evolution simulation.

Figure 8 shows the initial and numerical morphology of YRD in annual January from 1992 to 1995. The predicted development of the YRD can be found clearly in the figure, from January 1992 to September 1995, the mouth perimeter expanded nearly 20km, the newly-formed area is estimated to be 202 km^2. Figure 9 shows the bed level from the Qing VII cross-section to the mouth of the Yellow River. It can be found that the sediment does not deposit thickly on the river bed along the river way, but deposit thickly over the Mouth area. Dash-dot line is the measured bed morphology in January 1992 while dash line shows the measured bed morphology in September 1995, and the solid line is the numerical data splined with data along the river way from Qing VII (referring to Figure 2) to the Mouth in September 1995. We can see from the figure that the bed elevation on the river way rose just about 1.0 m during the four years while the Mouth moved forward into the sea altogether around 10km. The numerical results agree well with the measured data.

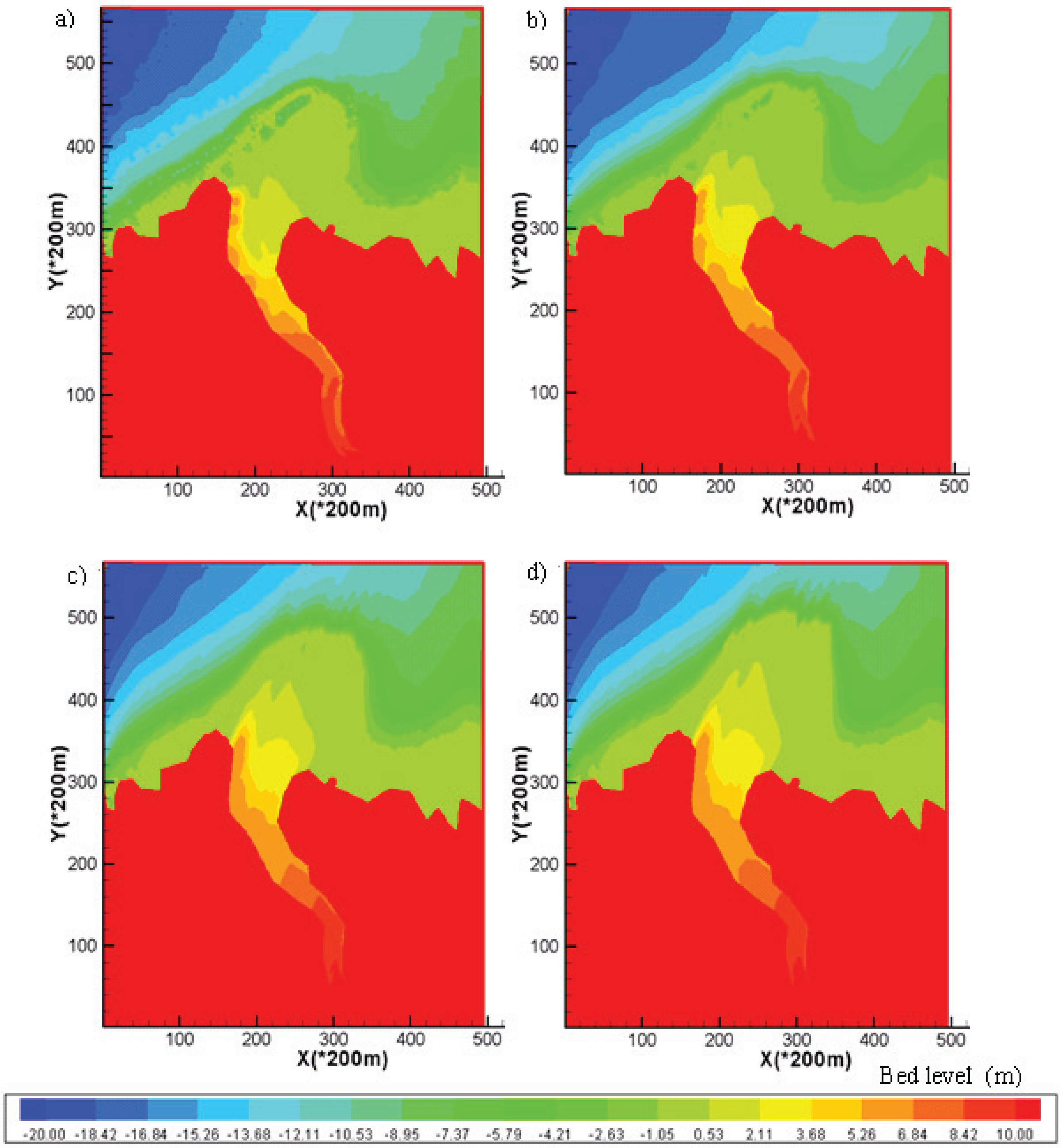

Figure 8 Morphology in the YRD, (a) Measured data in January of 1992; (b) Numerical data in January of 1993; (c) Numerical data in January of 1994; (d) Numerical data in January of 1995

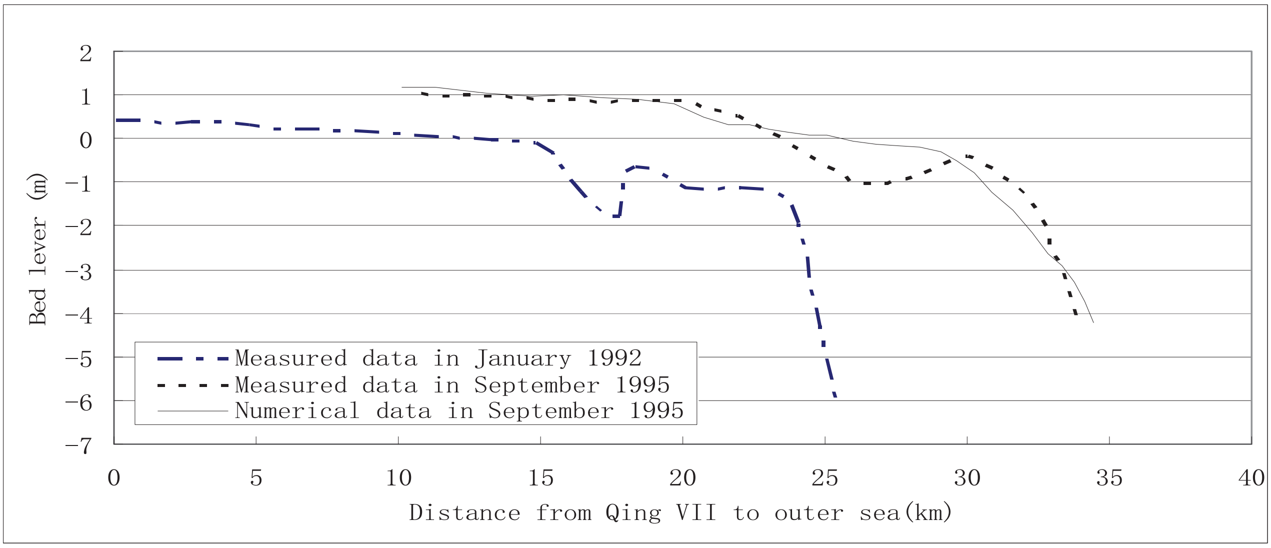

Figure 9 Bed level from Qing VII to outer sea

4. Conclusion

Details are given of the refinement of a two-dimensional depth-integrated numerical model for predicting bed evolution in estuarine and coastal waters. The model is capable of simulating the transport of graded sediments under unsteady flow and non-equilibrium conditions. A multiple bed layer approach is used to calculate bed level and sediment composition changes. The settling velocity is modified to account for the hindered effect in the high-concentration water

In order to validate the model, it is applied to the YRD. The hydrodynamic processes in the YRD are difficult to model because the inflow is varying greatly with the seasons, particularly large area along the river way is dry in winter time, the water contains very high sediment concentration, and most area has mobile bed layer due to sediment deposition. The present model is applied to solve such complicated environmental problems, and has obtained some reasonable results.

The hydrodynamic simulation and the sediment concentration on the river channel are both computed accurately, which is really fundamental for the longtime bed evolution computation. The predicted annual morphologies show the development process of YRD between 1992 and 1995, the mouth perimeter expanded nearly 20km, and the newly-formed area is estimated to be 202 km^2. According to the bed elevation from Qing VII to the mouth, sediment mainly deposits just out of the YRD, and the Mouth moves forward into the sea averagely 2.5 km annually. The formed and eroded land area of the Yellow River Estuarine wetland can be estimated with the method in this paper and it is ecologically important for protecting animals and vegetations in this foreshore wetland of the YRD.

5. Copyright

Acknowledgements

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