RESEARCH ARTICLE

Assessment of River Morphological Change for Co Chien Estuary Applying the CCHE2D Model

Seung Kyu Lee[1] · Truong An Dang[2] · Van Tuan Le[3]

Abstract

Two-dimensional (2D) numerical models are useful tools for studying river morphology. Frequently, 2D numerical models are often applied to predict the impacts of the artificial changes to rivers and estuaries. These changes may be caused by altered watershed hydrology, variations in the sediment supply and the construction of artificial works such as dams, embankments and tidal gutters. The aim of this study was to apply the CCHE2D model in simulating riverbed morphological variation in the Co Chien Estuary of Vietnam with complex morphology under the combined impacts of hydrodynamic processes such as waves, flow field, tidal currents and sediment transport. First, the proposed model was calibrated using water surface level and current speed data during dry and flood seasons in 2010. Calibrated results showed satisfactory coefficients (root mean square error smaller than 0.10 and Brier skill score (BSS) criteria varying between 0.63 and 0.94). Second, the proposed model is applied to simulate riverbed level variation for Co Chien Estuary after the 6-year flood (2010–2015). The results were evaluated comparing deviations between simulated and measured elevations at multiple monitoring cross sections and longitudinal bed profiles after the 6-year flood. Compared results confirmed that the proposed model is suitable for simulating hydrodynamic processes and riverbed morphological changes in the study area with BSS criteria greater than 0.68. The proposed model is a useful tool to help efficiently manage resources and minimizing the unwanted influences of wave, current, tide and sediment transport process.

Keywords CCHE2D · Sediment transport · Morphological · Aggradation · Degradation

Introduction

Large river estuaries often play an important role in the development of navigation, aquaculture and other socioeconomic activities (Ding and Wang 2008; Scott and Jia 2008; Hasan et al. 2007). To evaluate the performance of long-term strategies for protection of estuary areas, numerical models are considered an important tool for predicting the aggradation, degradation processes as well as river morphological variation driven by hydrodynamic factors such as flow fields, tidal current and wave (Ding et al. 2016; Scott and Jia 2008). According to Scott and Jia (2008) studies on river morphological change, 2D numerical models are needed for short-term river planning purposes and long-term river future projects (Lee and Dang 2018; Scott and Jia 2008). In general, numerical models are applied based on a combination of hydrodynamic and river morphological modules for simulating sediment transport processes and river morphological changes (Ding et al.

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2016; Sánchez et al. 2014). In recent years, depth-averaged 2D numerical models are widely applied because they can study long-term variations along both the longitudinal sections and cross sections of the rivers with minimal variation in river morphology (Dang and Park 2016b; Waters and Curran 2015), while one-dimensional (1D) numerical models only predict flow field and sediment transport in the longitudinal bed direction. For these reasons, 2D numerical models, namely Mike21, River-2D, Telemac-2D, Delft-2D, ECOMSED-2D and CCHE-2D, have been more appropriate for simulating 2D hydrodynamics and river morphological changes. While three-dimensional (3D) models are also considered an optimal selection (Kasvi et al. 2015; Wang et al. 2014) for simulating 2D hydrodynamics and river morphological changes, they can also simulate the flow field variations in the lateral, longitudinal and vertical directions. However, 3D models often require more input data information than 1D and 2D models (Kasvi et al. 2015; Wang et al. 2014). Therefore, 2D hydrodynamics and river morphology models are capable of predicting the full information of flow velocity components in the lateral and longitudinal directions and river morphological changes when they do not require the computation of the flow field in the longitudinal direction.

CCHE2D is a 2D hydrodynamic and sediment transport model which is constructed to simulate hydrodynamic processes, sediment transport and bedform formation for many river basins of the world such as the Mississippi and Arkansas Rivers (Duvoy and Toniolo 2012; Scott and Jia 2008), the Tanana River at Nenana, Alaska (Duvoy and Toniolo 2012), the Muda River in Malaysia (Hasan et al. 2007), the Connecticut River in New England (Ostfeld 2011), the Nile River (Nassar 2011), the Khoske Rud Farsan River in Iran (Fathi and Honarbakhsh 2013), the Gaoping River in Taiwan (Chao et al. 2016) and the Karkheh River in India (Kamanbedas et al. 2013). Specifically, Chao et al. (2016) applied the CCHE2D model to evaluate riverbed changes and sediment transport processes of the Gaoping River in the southern Taiwan under the impacts of climate change. They reported that the peak runoff discharge in the late twenty-first century could be 1.48 times larger than that in the late twentieth century. Fathi and Honarbakhsh (2013) used the CCHE2D model to simulate bank erosion in a natural river with high sediment loads and channel mobility named the Khoske Rud Farsan River in Iran. Simulated results obtained from the CCHE2D model showed its applicability for simulating bank erosion in the study area. Scott and Jia (2008) applied the CCHE2D model to simulate sediment transport and river morphological changes in large river systems of the Arkansas River and Mississippi Rivers in USA. The results have proven that the CCHE2D model can be a valuable tool for supporting the engineering decision making process on river engineering projects. Langendoen (2001) compared 2D numerical models such as CCHE2D, Delft2D, Mike21 and Telemac2D for simulating hydrodynamic, sediment transport capabilities and river morphological change. He reported that the CCHE2D model well simulates 2D hydrodynamics flow and sediment transport.

For this reason, this study selected the CCHE2D model with the main aim of evaluating the performance of the proposed model for simulating riverbed morphological changes under the combination of hydrodynamic factors, including wave, tide current, flow field and sediment transport in the Co Chien Estuary to help the local authorities in planning the important engineering projects to reshape the geometry of the estuary for providing the appropriate river bank protection solutions, against aggradation and degradation as well as river morphological changes.

Methodological Approach

Model Description

CCHE2D is a 2D hydrodynamic and sediment transport model for simulating unsteady open-channel flows over a loose bed (Ding et al. 2016; Duan et al. 2001). It was developed by the National Center for Computational Hydro-science and Engineering in the University of Mississippi (Wu 2001; Jia et al. 2002) based on the Navier–Stokes equations and sediment transport equations, and it has to deal with many actual physical and mathematical parameters. An advantage of the CCHE2D model is that it is easy to implement and simulate physical processes more accurately than other methods (Nassar 2011; Kamanbedas et al. 2013; Wu 2001). For these reasons, the CCHE2D model is widely applied nowadays for all types of real-life problems.

Governing Equations

CCHE2D is developed based on the Navier–Stokes and sediment transport equations to simulate unsteady flow, sediment transport and river morphological change in natural rivers (Ding and Wang 2008; Kamanbedas et al. 2013). The governing equations are given as follows:

$$\frac{\partial Z}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \tag{1}$$

$$\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -g\frac{\partial Z}{\partial x} + \frac{1}{h}\left[\frac{\partial(h\tau_{xx})}{\partial x} + \frac{\partial(h\tau_{xy})}{\partial y}\right]$$
$$- \frac{\tau_{bx}}{\rho h} + f_{\text{Cor}}v$$

$$(2)$$

$$\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -g\frac{\partial Z}{\partial y} + \frac{1}{h}\left[\frac{\partial(h\tau_{yx})}{\partial x} + \frac{\partial(h\tau_{yy})}{\partial y}\right]$$
$$- \frac{\tau_{by}}{\rho h} + f_{\text{Cor}}u$$

$$(3)$$

where h is the local water depth; u and v are the depth-integrated velocity components in the x and y directions, respectively, g is the gravitational acceleration; Z is the water surface elevation; ρ is the water density; τ_{xx}, τ_{xy}, τ_{yx} and τ_{yy} are the depth-integrated Reynolds stresses; and τ_{bx} and τ_{by} are shear stresses on the bed surface.

Sediment Transport Equations

In the CCHE2D model, the total load sediment is defined combining the bed load and suspended load transport formulas. The suspended load transport rate is given as follows:

$$\frac{\partial(hC_k)}{\partial t} + \frac{\partial(uhC_k)}{\partial x} + \frac{\partial(vhC_k)}{\partial y} = \frac{\partial}{\partial x}\left(\varepsilon_s h\frac{\partial C_k}{\partial x}\right)$$
$$+ \frac{\partial}{\partial y}\left(\varepsilon_s h\frac{\partial C_k}{\partial y}\right)$$
$$+ \alpha\omega_{sk}(C_{*k} - c) \quad (4)$$

where C_k is the concentration of the kth size class of sediment and C_{*k} is the suspended sediment.

And the bed load transport rate is defined as follows:

$$\frac{\partial(\delta_b\overline{c_{bk}})}{\partial t} + \frac{\partial(\alpha_{bx}q_{bkx})}{\partial x} + \frac{\partial(\alpha_{by}q_{bky})}{\partial y} + \frac{1}{L_t}(q_{bk} - q_{b*k}) = 0$$

$$(5)$$

where $\overline{c_{bk}}$ is the mean concentration of bed load, q_{bk} is the bed load transport rate of size class k, q_{b*k} is the bed load transport capacity 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.

Finally, the bed elevation variation is calculated by Eq. (6)

$$\left(1 - p'_m\right)\left(\frac{\partial z_b}{\partial t}\right)_k = \alpha\varpi_{sk}(C_k - C_{*k}) + (q_{bk} - C_{b*k})/L_s$$

$$(6)$$

where C_k is the concentration of the kth size class of sediment, C_{*k} and q_{b*k} are the suspended and bed load transport capacities, α is the adaptation coefficient of suspended load, ϖ_{sk} is the sediment setting velocity, p'_m is the porosity

of bed material, $\frac{\partial z_b}{\partial t}$ is the bed change and L_s is the adaptation length for bed load.

In the sediment transport module, the CCHE2D model is divided into suspended load and bed load (Duan and Julien 2010). The bed load and suspended load are considered as the part of the total sediment transport on or near the riverbed, and the total sediment transport then is defined by total of suspended load and bed load. Based on the views mentioned above, a full non-equilibrium transport module in the CCHE2D model is established for both bed load and suspended load to calculating sediment transport rate (Langendoen and Alonso 2008). The sediment transport rate is determined based on van Rijn's (1984) formula, Wu (2001) formula, SEDTRA module, the modified Ackers and White's formula or the modified Engelund and Hansen's formula (Carr et al. 2017; Wu 2001; Zhang 2013). A field survey indicated that grain size distribution in the study area is homogeneous; therefore, van Rijn's (1984) formula is considered the best match; so, in this work, van Rijn's (1984) formula is selected for calculating sediment transport rate.

van Rijn's (1984) formula is given as follows:

$$q_b = \alpha_b\rho_s Uh(d_{50}/h)^{1.2}(M \cdot e)^{\eta} \quad (7)$$

where q_b is the depth-integrated bed load transport (kg/s/m); $M \cdot e = (U - U_{cr})/[(s - 1)gd_{50}]^{0.5}$, U is the depth-averaged velocity (m/s); U_{cr} is the critical depth-averaged velocity for initiation of motion (m/s); d_{50} is the median particle size (m); h is the water depth (m); α_b is the coefficient; η is the exponent, ρ_s is the sediment density (kg/m³); $s = \rho_s/\rho_w$ is the specific density

An Application of the CCHE2D Model

The Study Area

The study area is one of the two main tributaries of the Tien River, flowing through the Vinh Long and Tra Vinh provinces of Vietnam. It has a length of about 55.0 km with average width approximately 1.0 km and is the border line between Vinh Long, Tra Vinh and Ben Tre provinces (Fig. 1). Co Chien Estuary begins from Vinh Long City, flowing in the northwest–southeast into the East Sea through the two major river branches of the Co Chien and Cung Hau. They are two of the significant inland waterway routes in the Mekong Delta of Vietnam with average water surface level (WSL) depth − 4.0 m. The mouth of the Co Chien River lies in the opposite direction of Ben Tre province and the mouth of the Cung Hau River lies away from the Tra Vinh province (Hanington et al. 2017).
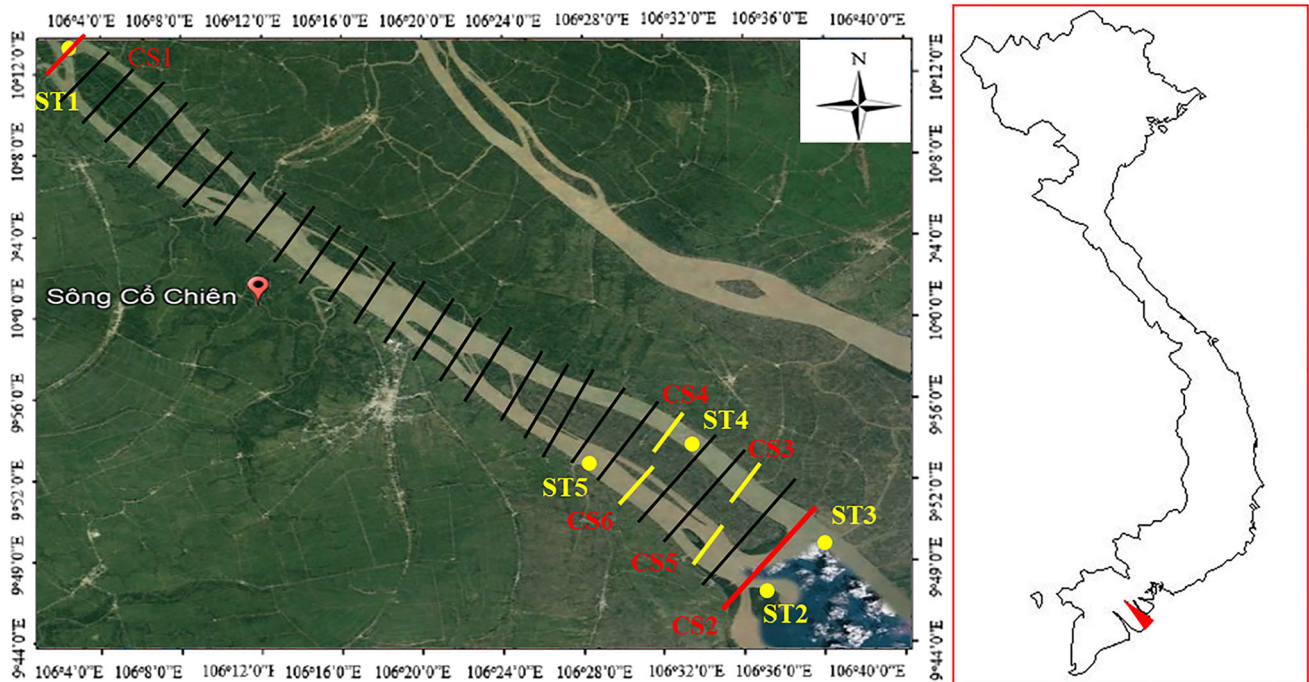
Fig. 1 Location of the Co Chien Estuary, including hydrologic stations

Between the two estuaries is the Thu islet with an area of approximately 44 km² and other small islets.

Data Collection and Model Setup

Initial Conditions

A field survey was conducted on the entire area on January 14, 2010, to collected bed topography data, WSL, current speed (CS), suspended sediment and bed load sampling (Fig. 2). To run a simulation, an important step in the procedure to set up the numerical models is to create a bathymetry grid. In this work, the hydraulic grid in the

initial state of the entire study area is designed by $I = 5.0$ m and $J = 50.0$ m, where $I_n \times J_{m-} = 230 \times 115,652$ cells, and the raw data are collected along multiple transects perpendicular to the direction of flow field using an echo-sounder device with the distance between two adjacent cells on each cross section of 5.0 m. The collected raw data are then used to establish a hydraulic grid using the CCHE-Mesh generation software; the hydraulic grid of the study area is presented in Fig. 3.

The WSL data series at ST1 (Cho Lach) and ST2 (Ben Trai) stations (Fig. 1) were collected from the National Center for Hydro-Meteorological Forecasting, Vietnam, to set up the upstream and downstream boundaries and ST4 and ST5 stations to calibrate the proposed model. Field surveys recorded that the average WSL values for many
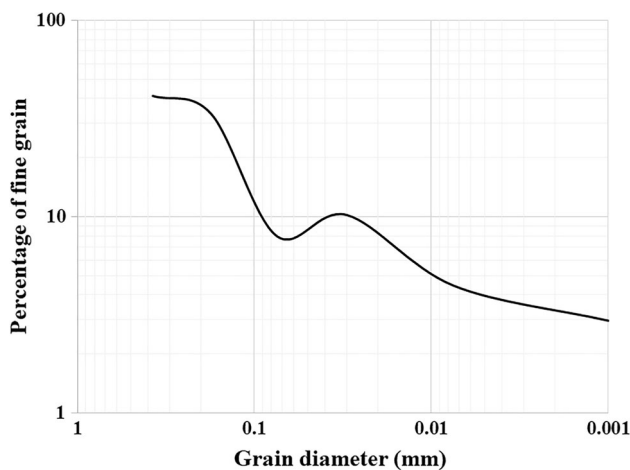

Fig. 2 Distribution of bed material curve for study area
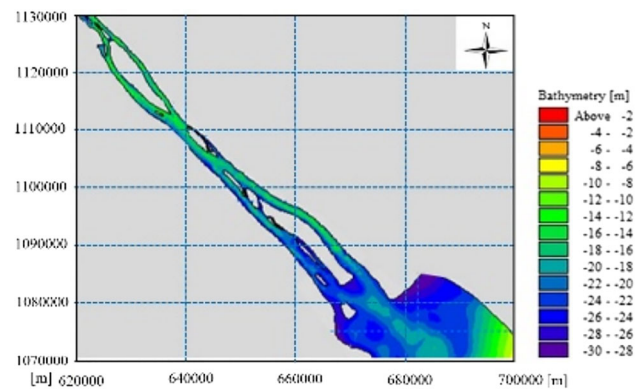

Fig. 3 Illustration of the hydraulic grid of the study river area

years at the upstream boundary in the dry and flood seasons were approximately 0.75 m and 1.25 m, respectively; therefore, to reduce simulation run time, the WSL at the upstream boundary is selected to approach the real WSL values. Specifically, the WSL at the downstream boundary in the dry and flood seasons was set equal to 0.5 m and 1.5 m corresponding to the beginning of the dry and flood seasons. Besides, the field survey is also conducted to collect bed topography data and the current speed, wave and discharge flow at CS3 and CS4 cross sections of the Co Chien River branch and CS5 and CS6 cross sections of Cung Hau River branch (Table 1) using the Echo-sounder and Acoustic Doppler Current Profile (ADCP) devices to set the upstream boundary, validation and calibration model.

The locations of WSL stations and cross sections were selected such that the survey positions were able to capture the WSL fluctuation and CS with the lowest error. The proposed model was calibrated using WSL and CS for the period from January 15 to May 15, 2010 (dry season), and August 15 to December 15, 2010 (flood season), and simulated RLV for the period from January 15, 2010, to January 15, 2015.

Model Performance Assessment

When a numerical model is applied to a field study, one has to calibrate the proposed model with field data. Because the real world is very complicated, one normally would not have the full input information, therefore, statistical methods, namely RMSE and BSS criteria, have been designed to assess certain desirable properties of forecasts (Nash and Sutcliffe 1970). According to Hanington et al. (2017), RMSE and BSS criteria are widely used to assess the model results with measured data (Guan et al. 2016; Hafezparast et al. 2013). RMSE and BSS criteria have determined the fit goodness to compare the model results with observed data (Lee and Dang 2018; Guan et al. 2016). RMSE was often selected to determine the absolute error

between the calculated and measured data. RMSE is described as follows:

$$RMSE = \sqrt{\frac{1}{n}(O_i - S_i)^2} \tag{8}$$

where O_i and S_i are the measured and simulated results at time i, respectively; n is the number of data points.

According to Waters and Curran (2015), the performance of numerical model for predicting water level and flow field is considered satisfactory if the values of RMSE are less than 0.5 while BSS is estimated as the most suitable criterion to assess the model performance (Guan et al. 2016; Jia and Wang 2001). BSS criteria are often used to evaluate the simulated riverbed level with measured data from a baseline.

BSS criteria are determined as follows:

$$BSS = 1 - \frac{\sum_{I=1}^{N}\left(Z_O^T - Z_S^T\right)^2}{\sum_{I=1}^{N}\left(Z_O^T - Z_S^{T=0}\right)^2} \tag{9}$$

where Z_O and Z_S are the observed and simulated bed levels, respectively; N is the total of grid points; and t is the time step

Classification ranges of the BSS criteria are given in Table 2.

Results and Discussion

Simulation Results of Water Surface Level (WSL)

In this work, the collected WSL data series at ST4 and ST5 and CS data series at CS2 and CS3 cross sections (Fig. 1) during the period of 12 months (from January to December 2010) are used to assess the model performance based on RMSE and BSS criteria. The simulated results of WSL at ST4 and ST5 stations in the two river branches of Co Chien and Cung Hau in the dry season (January 15–May 15, 2010) are shown in Fig. 3. During high tide stage in the dry season, tide currents speed can reach 0.95 m/s and 0.86 m/

Table 1 Data types used to set up, calibrate and validate the proposed model

Station	Longitude (°E)	Latitude (°N)	Data type		Purpose
			Water level	Current speed	
ST1	106°09′50″	10°11′51″	x		Upstream boundary
ST2	106°31′27″	09°53′02″	x		Downstream boundary
ST3	106°44′33″	09°54′03″	x		Upstream boundary
ST4	106°31′27″	09° 53′02″	x		Model calibration
ST5	106°26′29″	09°53′.33″	x		Model calibration
CS1	106°26′58″	09°56′19″		x	Model calibration
CS2	106°28′12″	09°52′06″		x	Model calibration
CS3	106°09′50″	10°11′51″		x	Upstream boundary

Table 2 Classification ranges for BSS values (Guan et al. 2016)

Classification ranges	Brier skill score
Excellent	1.0–0.8
Good	0.8–0.6
Reasonable	0.6–0.3
Poor	0.3–0.0

Table 3 Model performance for simulating water surface level and current speed based on BSS criteria and RMSE

Station	Data type	Model calibration			
		2010 low flood period		2010 high flood period	
		BSS criteria	RMSE	BSS criteria	RMSE
ST4	WSL	0.87	0.075	0.91	0.067
ST5	WSL	0.89	0.078	0.94	0.069
CS6	CS	0.67	0.083	0.68	0.091
CS3	CS	0.69	0.087	0.73	0.085

s, respectively, at ST4 and ST5 stations, while at the ebb current, tide current speed only reaches 0.55 m/s and 0.36 m/s, respectively, at ST4 and ST5 stations, respectively. In addition, simulated results also found that a complex tidal current pattern exists in the study area with a mix of diurnal from the East sea and semidiurnal tides from the West sea and the strong influence of the flow field from the upper Mekong River.

Calibration of WSL is reliable with the BSS criteria and RMSE at ST4 station (Fig. 4a) being 0.87 and 0.085, respectively, while at ST5 station (Fig. 3b) they are 0.89 and 0.088, respectively (Table 3). In general, the model performance showed agreement between predicted and measured WSL at ST4 and ST5 stations during the dry season.

Similarly, the results of WSL at ST4 and ST5 stations in the flood season (August 15–December 15, 2010) are shown in Fig. 5a, b. During the high tide stage in the flood season, tide current speed can reach 0.95 m/s and 0.86 m/s at ST4 and ST5 stations, respectively, while at the ebb current stage, tide current speed only reaches 0.55 m/s and 0.36 m/s at ST4 and ST5 stations, respectively. Calibration results of WSL are reliable with RMSE at ST4 and ST5 stations being 0.067 and 0.069, respectively (Fig. 4a, b). In general, model performance also showed agreement

between predicted and measured WSL at ST4 and ST5 stations during in the flood season.
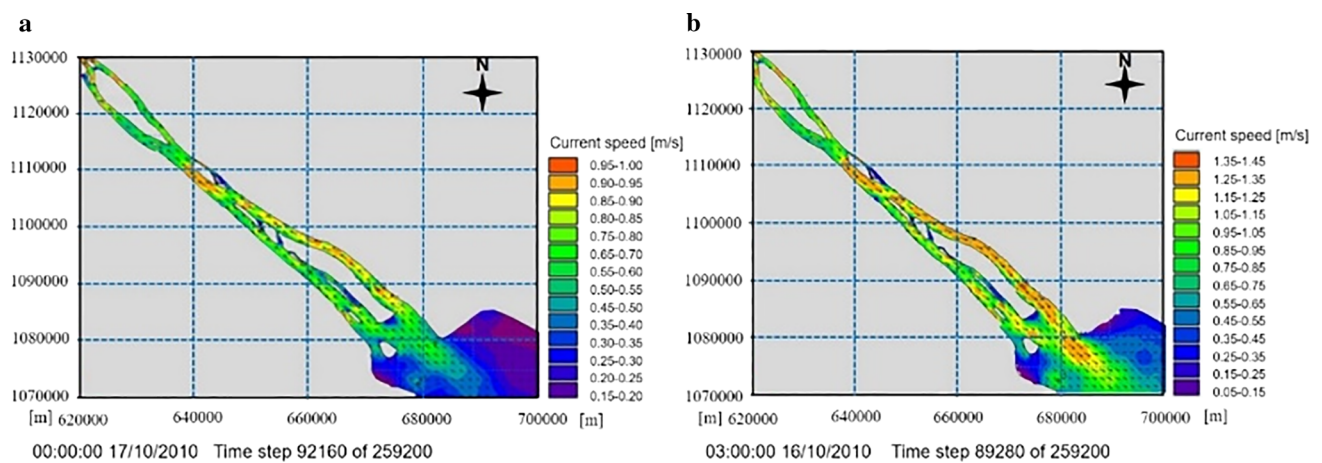
Simulation Results of Current Speed (CS)

The results of CS during the high flood season (August 15–December 15, 2010) showed that both tide current speed when high tide and ebb current speed combined with flow field at ST4 and ST5 stations of the two river branches are the same phase (Fig. 6). During the high tide stage, maximum tide current speed can reach approximately 0.85–0.90 m/s (Fig. 6a), while maximum ebb current speed combined with flow field can reach 1.25–1.35 m/s (Fig. 6b). The flow field at the end of the Cung Hau River branch is approximately 1.27 m/s, while at the same location of the Co Chien River branch, this value only reaches 1.06 m/s. In general, results of the flow field distribution are consistent with survey data because the depth of the riverbed in the Co Chien River branch is less than the Cung Hau River branch, and the flow field at the Co Chien River branch, therefore, is lower than in the Cung Hau River branch.
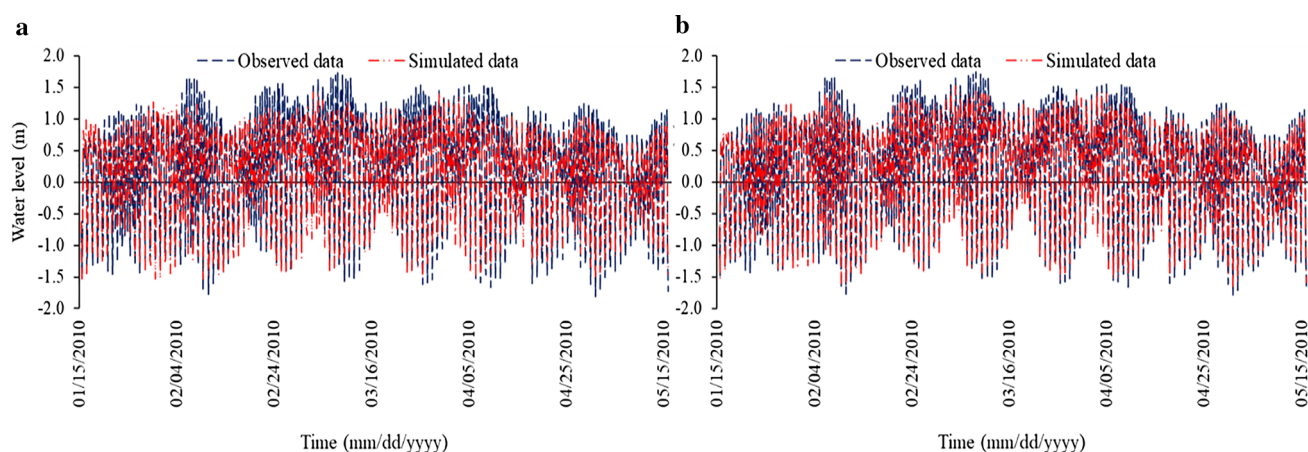
Fig. 4 Comparison of simulated and observed water surface level at **a** ST4 and **b** ST5 stations on in the dry season with RMSE = 0.075 and 0.078 and BSS = 0.87 and 0.89, respectively
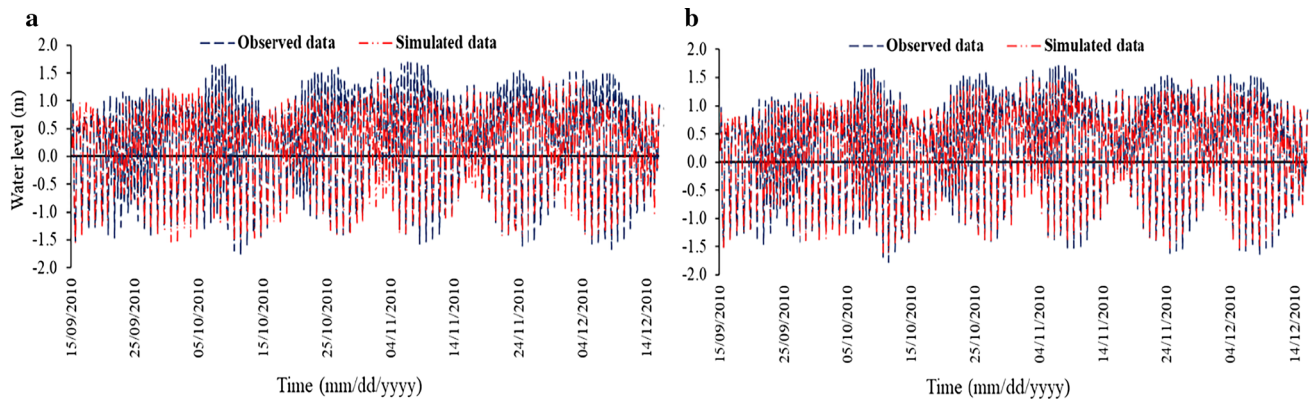
Fig. 5 Comparison of observed and simulated water surface level at **a** ST4 and **b** ST5 stations on in the flood season with RMSE = 0.067 and 0.069 and BSS = 0.91 and 0.94, respectively

Fig. 6 Simulated results of current speed at **a** high tide and **b** low tide in the flood season of the high flood year in 2010

In the dry season, the results of the flow field from the model are presented in Fig. 7. It can be seen that the speed of the tide current when high tide and ebb current at ST4 station of the Co Chien River branch and ST5 station of the Cung Hau River branch is also recorded as the same phase.

Maximum tide current speed when high tide (at 03:00:00 on 27 Mar 2010) reached approximately 0.90–0.95 m/s (Fig. 7a), while ebb tidal current (at 03:00:00 on 23 Mar 2010) combined with flow field from the upper Mekong River reached approximately 1.15–1.25 m/s (Fig. 7b).
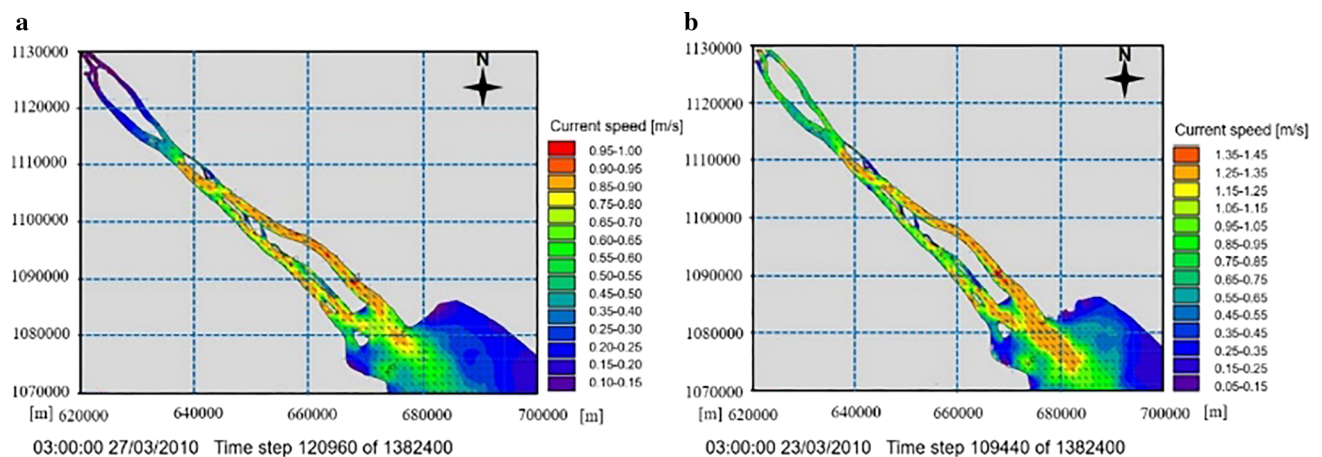
Fig. 7 Simulated results of current speed at **a** low tide and **b** high tide stages in the dry season of high flood year in 2010

Simulation Results of Riverbed Level Variation (RLV)

Figure 8 presents the results of RLV at CS5 and CS6 cross sections of the Cung Hau River branch (a distance of 18.5 km and 5.0 km, respectively, from the downstream boundary) after the 6-year flood. Results of RLV defined the aggradation tendency compared with the initial riverbed level (IRL) with average aggradation at CS5 cross section was approximately 0.63 m, while this value of the IRL after the 6-year flood was 0.43 m (Table 4). In contrast, a slight degradation tendency was found at CS6 cross section with 0.61 m compared with IRL, while the measured value of the final riverbed level (FRL) after the 6-year flood was 0.48 m (Table 4).

Figure 9 shows the simulated results of RLV at CS3 and CS4 cross sections of the Co Chien River branch (a distance of 22 km and 7.5 km, respectively, from the downstream boundary). The results are also recorded aggradation tendency at CS3 cross section compared with IRL with an average value was 0.18 m, while FRL after the 6-year flood is aggraded 0.14 m (Table 4). A slight degradation tendency compared with IRL is also found at CS4 cross section, which was 0.17 m, while the measured data of the FRL after the 6-year flood were 0.13 m (Table 4).

In general, the simulated results of RLV at CS3 and CS4 cross sections of the Co Chien River branch, CS5 and CS6 cross sections of the Cung Hau River branch indicated that the CCHE2D model was in good agreement with BSS criteria, which varied from 0.69 to 0.81 (Table 4).

The results of RLV over the entire study area in the longitudinal bed profiles (LBP) after the 6-year flood (2010–2015) are illustrated in Fig. 10. The results show that at a distance of 30 km and 35 km from the entrance to both Cung Hau and Co Chien River branches a slight aggradation occurred with a range from 0.53 to 0.38 m, while the observed data were 0.44 m and 0.31 m,

respectively. In contrast, the significant degradation occurred at a distance from 31 km of Cung Hau River branch and 36 km of Co Chien River branch away from the entrance to the mouth; the river bed showed degradation with average degradation depth approximately 0.61 m and 0.37 m, while the observed data were 0.49 m and 0.79 m, respectively. In general, over the entire LBP after the 6-year flood for both Co Chien and Cung Hau River branches occurred the aggradation with average depth varied from 0.14 to 0.25 m, respectively, while the observed data were 0.45 m and 0.33 m, respectively (Table 4 and Fig. 10).

Model performance for simulating RLV in the LBP evaluated based on the BSS criteria for the Co Chien River branch case was 0.63 (Fig. 10a) and for the Cung Hau River branch was 0.78 (Fig. 10b), which means that the simulated results of the proposed model for RLV in the LBP of the Co Chien River branch were not good enough. A field survey indicated that one of the main causes is due to artificial activities on the riverbed.

Conclusion

The results of water surface level and current speed for both the dry and flood seasons were in good agreement with surveyed data at all water surface level stations (ST4 and ST5) and cross sections (CS3 and CS6) with values of RMSE and BSS criteria corresponding to water surface level varying from 0.065 to 0.078 and current speed varying from 0.87 to 0.89, respectively.

Compared results of riverbed level variation on cross sections and longitudinal bed profiles for both Co Chien and Cung Hau River branches confirmed that the proposed model is a good simulation with BSS criteria for cross sections in the range 0.69–0.81 and 0.63–0.78, respectively.
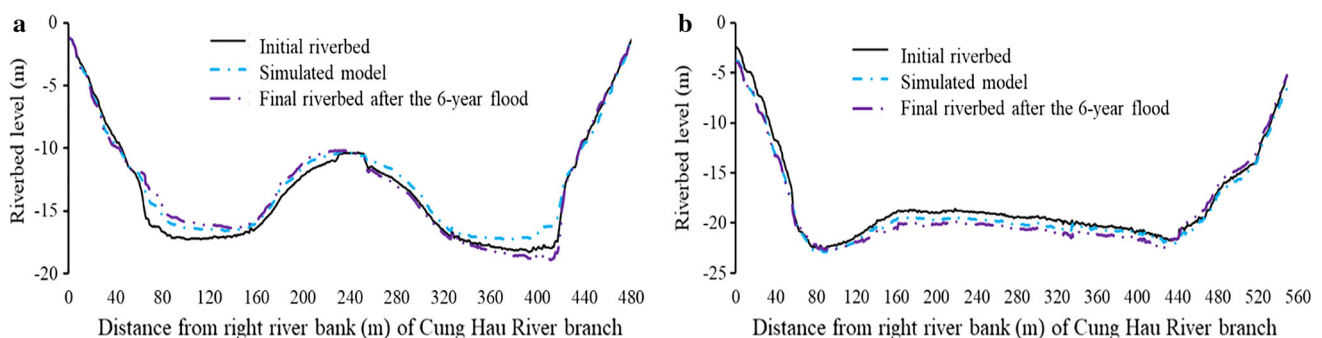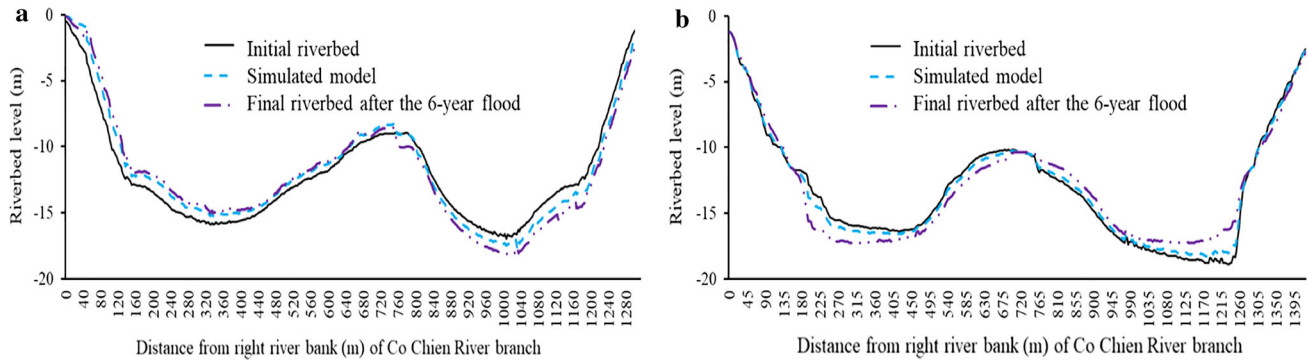

Fig. 8 Comparison of the proposed model and measured riverbed level after the 6-year flood at **a** CS5 cross section of the Cung Hau River branch where distance is 18.5 km from the downstream and

b CS6 cross section where distance is 5.0 km from the downstream with BSS = 0.81 and 0.74, respectively

Table 4 Comparison of calculated and measured results of riverbed level after the 6-year flood with IRL at cross sections and longitudinal bed profiles (LBP)

Cross section	Measured data (m)	Simulated model (m)	BSS criteria
CS3	0.44	0.18	0.69
CS4	0.31	0.17	0.73
CS5	0.43	0.59	0.81
CS6	0.48	0.61	0.74
LBP1	0.45	0.14	0.63
LBP2	0.33	0.25	0.78

Fig. 9 Comparison of the proposed model and measured riverbed level variation after the 6-year flood at **a** CS3 cross section of the Co Chien River branch where distance is 22.0 km from the downstream boundary and **b** CS4 cross section where distance is 7.5 km from the downstream boundary with BSS = 0.69 and 0.73, respectively

Fig. 10 Riverbed level variation in longitudinal bed profiles at **a** Co Chien River branch and **b** Cung Hau River branch before and after the 6-year flood with the BSS criteria = 0.78 and 0.63, respectively
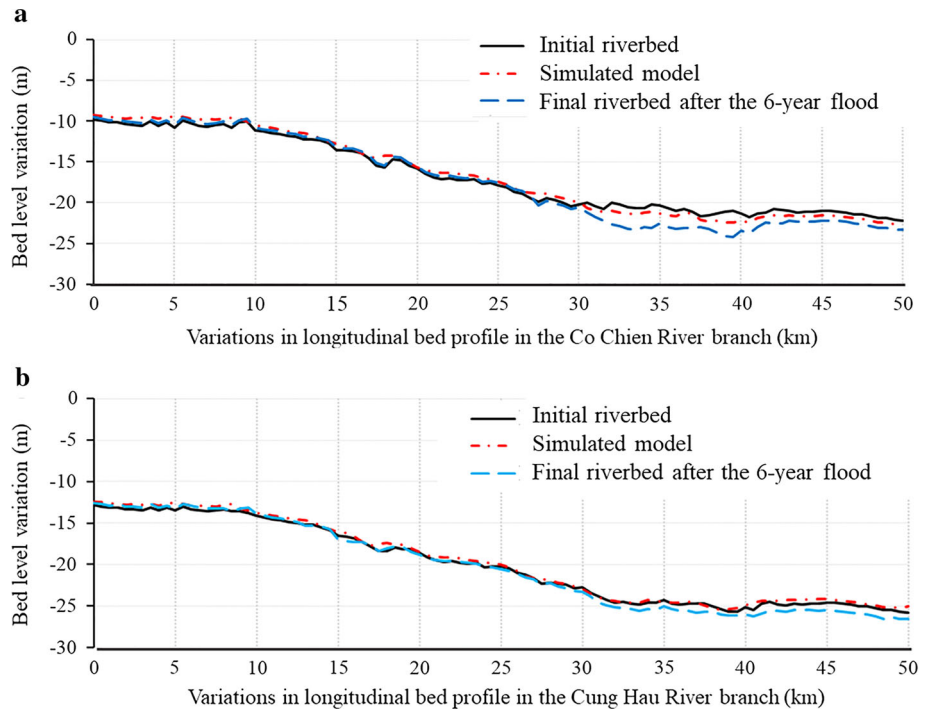
The study found that the proposed model can accurately represent long-duration variation in the horizontal and LBP in large estuaries where degradation and aggradation processes are intertwined and very complex.

The results confirm that the CCHE2D model's performance and its application are very appropriate for engineering projects. The results provide the useful information to help agencies decide to implement river bank protection projects for reducing damage.

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