JARQ 47 (4), 405 - 415 (2013) http://www.jircas.affrc.go.jp

The Effect of Simulated Sea Level on the Sedimentation of the Tien River Estuaries, Lower Mekong River, Southern Vietnam

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Abstract

Owing to global warming, sea-level rise (SLR) poses a serious threat to low-lying coastal areas. The potential impacts of SLR include inundation, coastal erosion, salinity intrusion, and degradation of coastal habitat. The Mekong River Delta (MRD) in southern Vietnam is a flat, low-lying land area that has experienced significant effects of climate change and SLR. Sea-level data collected from 1979 to 2006 show that the highest mean surface level of the spring tide has risen by 13 cm. This study investigated the impacts of climate change and SLR on sedimentation processes in the Tien River Estuaries of the Mekong River System. Long-term simulation results were obtained for the baseline and two SLR scenarios. In the low-SLR scenario, morphological evolutions of the Tien River Estuaries showed the same trend as the existing processes in the baseline, but intensified erosion and deposition processes. In the high-SLR scenario, the processes of erosion and deposition become too complex to estimate.

Discipline: Agricultural Engineering
Additional key words: Mekong River Delta, Mike 21 Coupled FM, Sediment transport

Introduction

The processes of erosion and deposition in a river estuary are extremely complex[1,5,6,7,8,9,13,17,24,27,30,32,31,34]. Evolution of the morphology of the estuary results in both positive and negative contributions to the environment and economy, such as the development of agriculture and aquatic products such as shellfish and other fish. Erosion may decrease the fertility of the land and even damage the livelihoods of local people, whereas the deposition of sediment can form new alluvial land or expand existing islets, dunes, and sandbars. However, such deposition may also cause serious problems for navigation, such as closing of the river or estuary. It is therefore important to recognize that deposition processes pose significant challenges for the sustainable management of water resources. Sedimentation is a vital concern for the conservation, development, and utilization of soil and water resources[6,13].

Vietnam is well known as a country with numerous rivers and has two large deltas created by two of the longest rivers in Asia: the Red River and the Mekong River. The Red River forms the northern delta, while the Mekong River with its main distributaries, the Tien River and Hau River, creates the southern delta. The Mekong River Delta (MRD) is flat, low-lying, and fertile and has hence contributed significantly to the development of the social economy, supporting 16 million inhabitants (approximately 22% of the total population of Vietnam), providing more than 27% of the country's GDP and about 50% of the annual rice production[2,10,28]. From the last decades of the 20th century to date, the MRD has been affected by concentrated human activities, rapid economic development, and climate change in particular, resulting in major land and water resource problems such as acute flooding during the wet season, seawater intrusion in the lower delta during the dry season, and sedimentation and erosion. The complex morphological evolutions of the Mekong River Estuaries are among the

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Received 5 July 2012; accepted 20 February 2013.

most serious influences.

In recent decades, a number of studies have provided new and interesting results. These noteworthy publications include Wolanski *et al*. (1996, 1998)[35,36]; Nguyen (1995)[19]; Nguyen *et al*. (2000)[22]; Ta *et al*. (2000, 2001)[25]; Nguyen (2007)[21]; Tamura *et al*. (2010)[26]; Mikhailov and Arakelyants (2010)[18] and Tran and Tran (2008)[29]. It was pointed out that most of the suspended sediment (SS) is fine silt and that sediment transport is influenced by many factors, particularly river currents, sea currents (monsoon currents), tidal currents, and wave-generated currents. Furthermore, the combination of meteorological and oceanic effects produces strong variations in coastal areas, mainly at seawater level and coastal currents.

According to the Intergovernmental Panel on Climate Change (IPCC)[11,12], the coastal countries of Southeast Asia are highly vulnerable to climate change. Of these, Vietnam ranks first in terms of population among ten countries and territories that could be impacted by sea-level rise (SLR). Global climate change and SLR could alter the hydrodynamic characteristics of low-lying coastal areas such as the MRD. Hence, the morphological evolution of the Mekong River Estuaries is related to urgent challenges of sustainable development and protection of human society[11]. In this study, we simulated erosional and depositional processes in the Tien River Estuaries, Mekong River System, including the effects of SLR. To calibrate the model, simulated results were compared with observed data from 2009. Two assumption scenarios, low- and high-SLR in southern Vietnam, based on the key project of state KC.08.06.10 (Nguyen, Q. K., 2010)[20] and computed for a period of one decade from 1 January, 2010 to 1 January, 2020, were used to investigate morphological processes in the Tien River Estuaries.

Geological Setting and Methodology

1. Study area

The Mekong River, stretching from the snowy mountains of Tibet to the South China Sea, is one of the longest in Asia. The total area of the watershed is about 795,000 km^2 and it is about 4,800 km long. The Mekong has various meteorological regimes between dry and wet seasons and its average discharge is about 15,000 m^3/s, ranking it ninth largest in the world. When the Mekong River enters Vietnam, it splits into two primary distributaries, the Tien River (Mekong River) and the Hau River (Bassac River). These two rivers germinate into a dense river network on the low plain of southern Vietnam.

In its upstream section, the Tien River carries about 80% of the total discharge of the Mekong River. Subsequently however, its discharge decreases significantly due to transferring a large volume of water to the Hau River via the Vamnao River. The Hau River flows straight to the South China Sea through two estuaries, but the current of the Tien River, owing to the imprint of its geological setting, is oscillatory and tortuous before emptying into the South China Sea through six estuaries. In this study, the estuaries of the Tien River were modeled to simulate its morphological evolution, as shown in Fig. 1. However, the

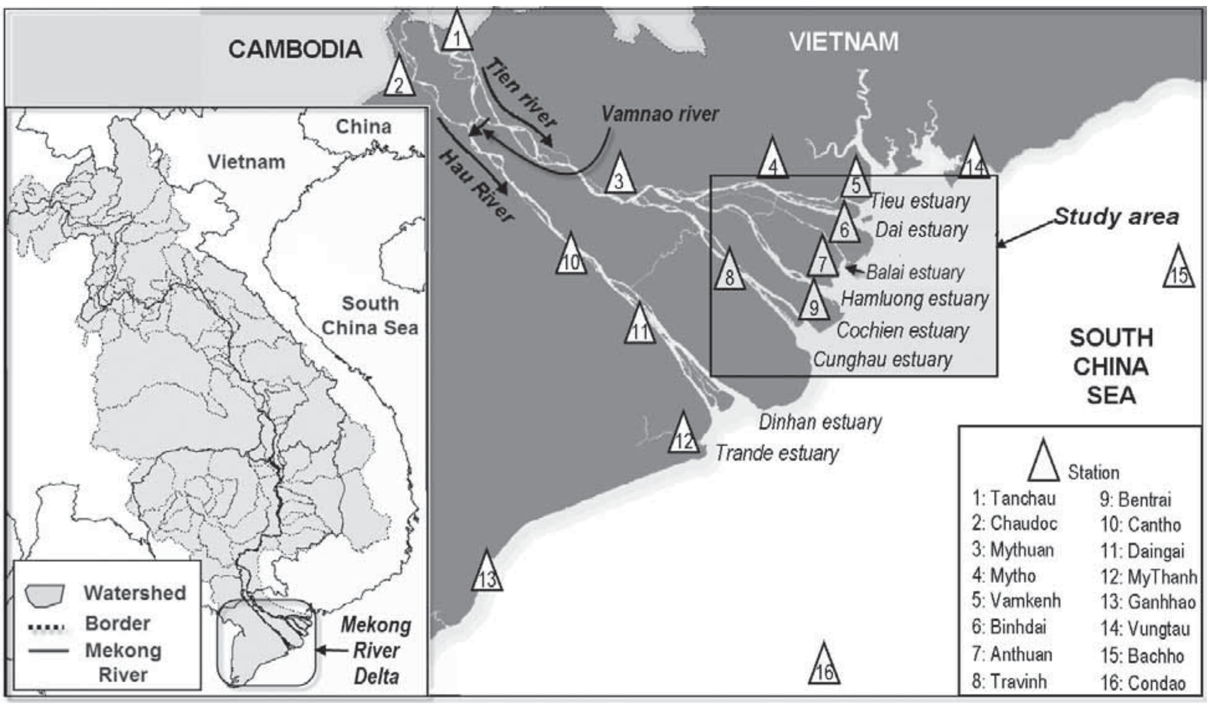

Fig. 1. Location of the Lower Mekong River and hydrological stations in southern Vietnam

Table 1. Sea-level rise (cm) relative to the period 1980–1999

Scenario	2020	2030	2040	2050	2060	2070	2080	2090	2100
Low SLR scenario	11	17	23	28	35	42	50	57	65
Medium SLR scenario	12	17	23	30	37	46	54	64	75
High SLR scenario	12	17	24	33	44	57	71	86	100

BaLai Estuary, which was nearly closed by hydraulic construction, was not considered.

2. Proposed modeling scenarios

The Vietnam Ministry of Natural Resources and Environment (MONRE, 2009)[33] reported that the sea level may rise by 28 to 33 cm in 2050 and about 65 to 100 cm in 2100, relative to the baseline period of 1980–1999 (Table 1). SLR will tend to exacerbate the effects of coastal erosion and deposition. In addition, it may cause the river's discharge to vary, resulting in strong sea-current domination at the river mouth, which could aggravate the problem of salt intrusion. In this study, two scenarios, low- and high-SLR, designed with increases in sea level of 30 cm (in 2050) and 100 cm (in 2100), respectively, were used to simulate morphological processes in the Tien River Estuaries.

3. Description of the Mike 21/3 Coupled Model FM model

The MIKE 21/3 Coupled Model FM[3] is a dynamic modeling system applicable within coastal and estuarine environments. The MIKE 21/3 Coupled Model FM comprises several modules: the Hydrodynamic Module, Spectral Wave Module, Mud Transport Module, Sand Transport Module, etc. The mutual interaction between waves and currents can be simulated using dynamic coupling between the Hydrodynamic Module and Spectral Wave Module. The MIKE 21/3 Coupled Model FM also includes dynamic coupling between the Mud Transport, Sand Transport, Hydrodynamic, and Spectral Wave modules. This means full feedback of bed-level changes in wave and flow calculations can be included[4,5]. This research used several modules of the system, such as the Mike 21 Hydrodynamic Module FM (Mike 21 HD), the Spectral Wave FM Module (Mike 21 SW), and the Mud Transport Module (Mike 21 MT) to study the morphological evolution of the Tien River Estuaries.

4. Applying the model and evaluating the calibrated results

Two models were developed: a regional model covering the South China Sea in southern Vietnam (Fig. 2) and a local model of the Mekong River Estuaries (Fig. 3). The boundaries of the regional model are specified as from the Mekong River mouths to the Bachho and Condao hydrographic stations (Fig. 2), where limited wave data are available. The local model covers a region from the Mythuan and Cantho (Fig. 2) to the nearshore zone of the Mekong River Estuaries. The local and regional models covered a mesh area sufficient to ensure that the impacts of the main factors on the wider area were fully considered. To link up the local and regional models, the downstream boundary conditions of the local model, such as water level and waves, are extracted from the large regional model.

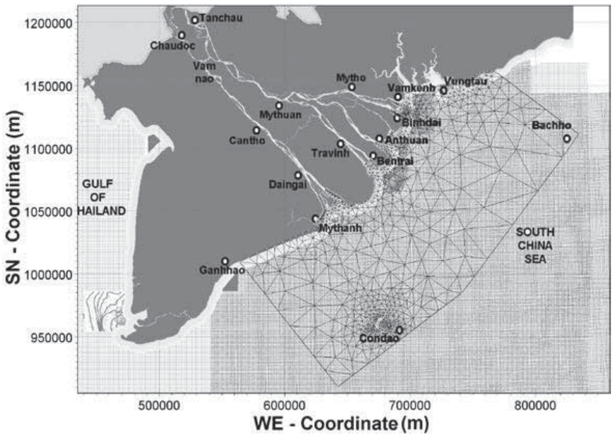

Fig. 2. Regional model with unstructured mesh

These two models of the Tien River's estuaries were first calibrated with the observed water level, velocity, wave, and suspended sediment (SS) data, in September 2009. In the regional model, the upstream boundary conditions were the water level series of the hydrological stations at the Mekong River mouths (e.g. Vungtau, Vamkenh, Binhdai, Anthuan, Bentrai, Mythanh, and Ganhhao), whereas predicted tidal elevations were used for the downstream boundaries. The monthly input data of wind speed and direction were based on data measured from the Vungtau meteorological station. The monthly average wave data from the Bachho station were specified for the offshore wave boundary conditions. The two hourly upstream discharge boundaries in the local model were the Mythuan and Cantho hydrological stations. At the downstream end, the water level and spectral wave boundaries in the sea were obtained by results from the regional model. In the upstream area, salinity boundaries were set at 0‰ year-round. In the coastal zone, these boundaries were 32‰, except in January and February when the boundaries were set at 35‰[18,20]. In

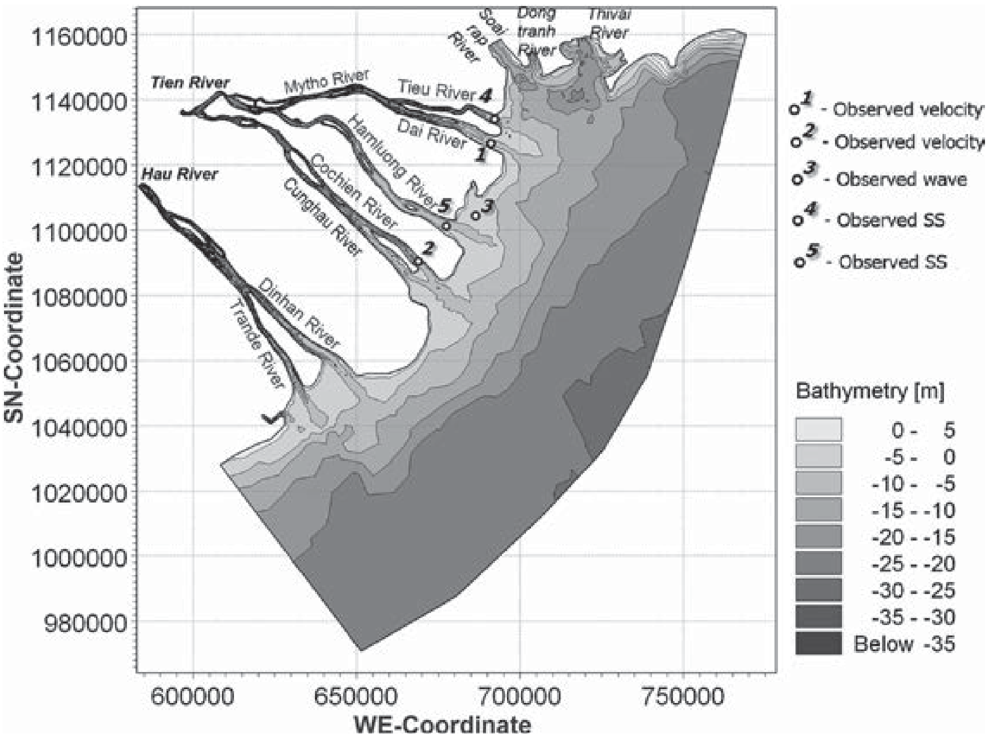

Fig. 3. Bathymetric of local model covering the Mekong River Estuaries

addition, since the temperature ranged from 24 to 28°C over the whole area, the value of 26°C was selected.

The calibrated parameters of the Mike 21 HD, Mike 21 SW, and Mike 21 MT models were fixed to gain appropriate results. In Mike 21 HD, density was considered a function of temperature and salinity, and the Manning value is within the range 20–40 $m^{1/3}/s$ by variation in the water depth. The time step was from 0.1 to 30 s and defined by separation of the Courant–Friedrich–Levy (CFL) stability criterion; the CFL number was 0.9. The Eddy viscosity was specified by the Smagorinsky formulation with a Smagorinsky coefficient value of 0.28[3,14,15,16]. In Mike 21 SW, the decoupled parametric formulation was selected to simulate waves by Nikuradse roughness and the JONSWAP formulation[4].

In Mike 21 MT, after trial-and-error processing, the achieved fall velocity of suspended sediment was 0.2 mm/s. According to analysis of the bed parameter of the Mekong River Estuaries, the model bed was described by four unique layers: a surface mud layer as a mobile fluid mud with low critical shear stress of erosion, a second mud layer as partly-consolidated mud, a third consolidated mud layer with high-density sediment, and a fourth hard mud layer. Erosion was calculated using an equation originally proposed by Parchure and Mehta (1985)[23], which is given below:

$$SE = E \times e^{[\alpha \times \sqrt{\tau_b - \tau_{cre}}\,]} \qquad (1)$$

where S_E is the erosion rate (g/m^2), E is the erodibility of the bed ($kg/m^2/s$), α is the erosion coefficient ($m/N^{0.5}$), τ_b is the bed shear stress (N/m^2), and τ_{crs} is the critical bed shear stress for erosion (N/m^2).

The parameter values of each layer were based on the results of Letrung (2012)[14], as shown in Table 2. For sediment boundaries, the mean seasonal SS values at Mythuan and Cantho were used as upstream boundaries and downstream boundaries in the South China Sea with an average SS of 0.0001 g/L.

Figure 4 shows the calibrated results from September 18–21, 2009, in the Dai and Cochien Estuaries of the Tien River. Figures 4a and 4c show a comparison between simulated water levels and observed data (Binhdai and Bentrai) with very little deviation (less than 5%) and similar fluctuations in variation. Simulated current speed results show good agreement with observed data, as shown in Figs. 4b (point 1 in Fig. 3) and 4d (point 2 in Fig. 3). These two figures delineated the same order between simulated velocity results and observed data, and there was no noticeable difference between the series. Figure 5 shows the simulated result and observed data north of the Hamluong Estuary (point 3 in Fig. 3). This figure indicates that the two series were close and that the simulated results were satisfactory. In general, the simulated results virtually replicated the particularity of waves in the study area, despite small discrepancies in the observed data.

The calibrated SS results from the mud transport module and observed data of the Tieu and Hamluong estuaries,

Table 2. Bed parameters in Mike 21 MT

Layer number	Mud Type	Wet Density of bottom sediment (g/L)	Critical shear stress for Erosion τ_{cre} (N/m^2)	Erosion coefficient E (kg/m^2/s)	Coefficient α (m/N$^{0.5}$)	Initial thickness (m)
1	Mobile fluid mud	120	0.17-0.20	0.000005	5	0.05-0.3
2	Partly consolidated mud	300	0.35-0.40	0.000001	4	1-2
3	Partly consolidated mud	450	0.55-0.60	0.000001	4	4-6
4	Hard mud	600	1.50	0.0001	1	10

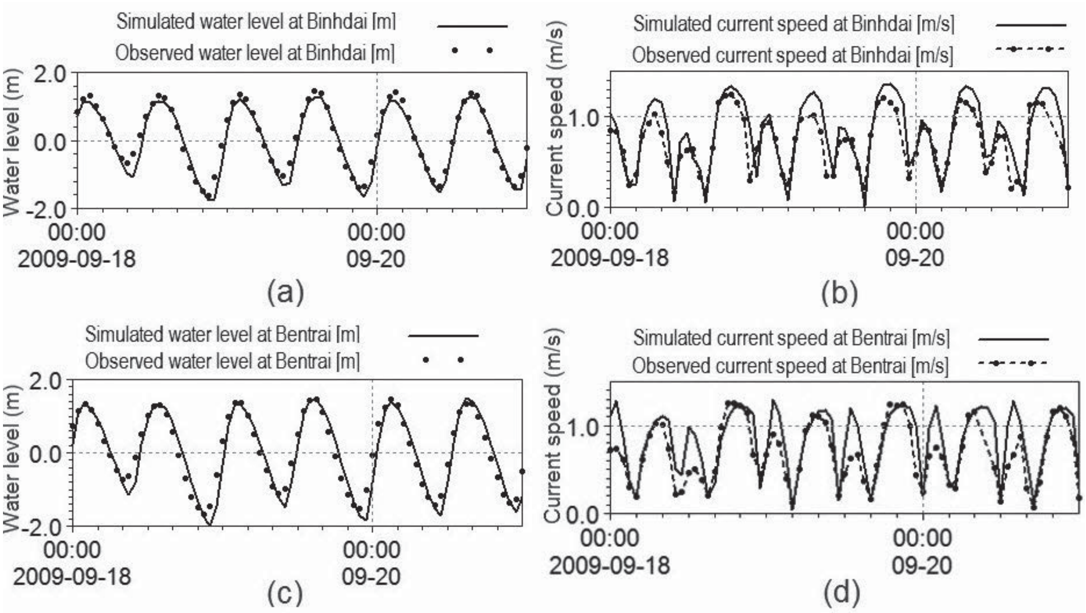

Fig. 4. Calibration of water levels and current speeds simulated by Mike 21 HD

shown in Fig. 6, were obtained for the same calibration time with hydrodynamics. Those figures showed that the simulated results and observed data for each estuary were similar and concurrent. Although the maximum observed data exceeded the simulated results, this was to an insignificant extent, whereas the minimum survey data and simulated results had the same value.

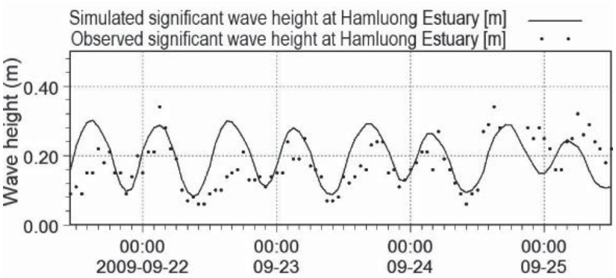

Fig. 5. Calibration of significant wave heights simulated by Mike 21 SW at point 3 in Fig. 3

Results and Conclusions

1. Simulating the SLR scenarios and results

Comprehensive calibrations between simulated results and observed hydrodynamics data (i.e. water level and current speeds), waves, and movement of sediment in September 2009 conducted through simulation by the Mike 21 Coupled FM achieved appropriate results and indicated that the selected parameters were reasonable. Next, the two models were simulated for three cases: the baseline and the low- and high-SLR scenarios. These scenarios were computed for a decade from January 1, 2010 to January 1, 2020.

The computed astronomical tide and resulting time series of water levels were used for upstream (river mouths) and the sea boundaries of the regional model in the baseline, whereas the boundary conditions in the two SLR scenarios were based on the results obtained in the key projects of Nguyen (2010)[20] and Letrung (2011, 2012)[14,15]. Next, the results of the regional model were extracted and set as the downstream boundary conditions of the local model. The time series of the mean hourly discharge of the Tien (My Thuan hydrological station) and Hau Rivers (Can Tho hydrological station) were the upstream boundary condi-

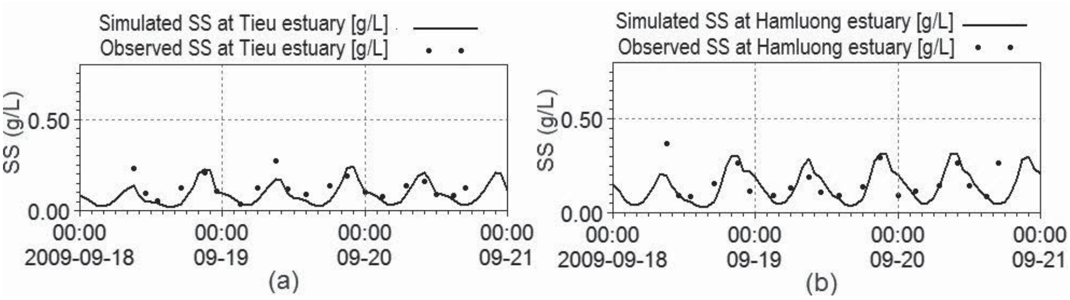

Fig. 6. Calibration of suspended sediment concentrations simulated by Mike 21 MT

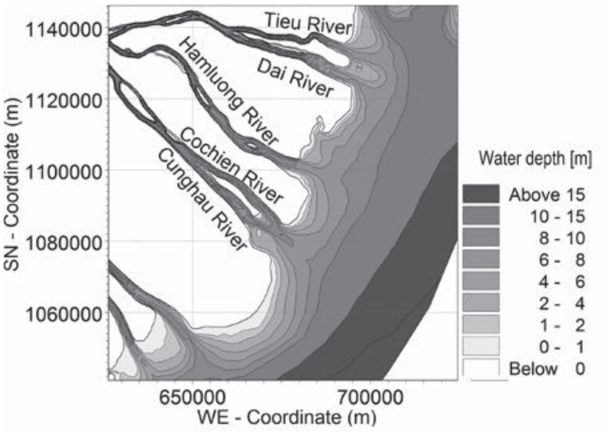

Fig. 7. Water depth simulated in the baseline at 18:00 (GMT +7) on January 20, 2012

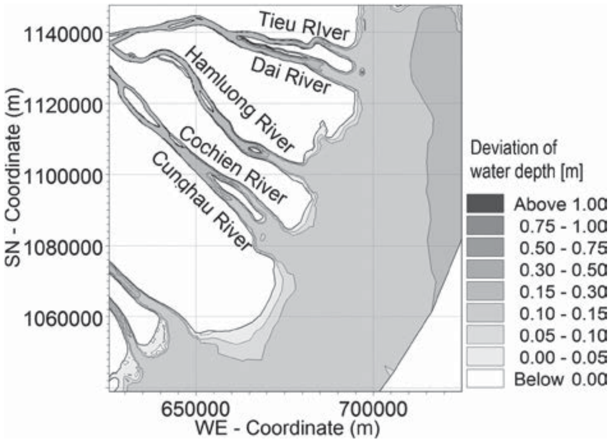

Fig. 8. The deviation of simulated water depth between the low-SLR scenario and the baseline at 18:00 (GMT +7) on January 20, 2012

tions for the local model.

The hydrodynamic modeling results indicated marked differences among the three simulation scenarios and significant influences of SLR on the currents of the Tien River Estuaries. The water depth of the baseline ebb tide and the deviation of water depth in the low- and high-SLR scenarios compared with the baseline are shown in Figs. 7, 8, and 9, respectively, for the dry season of 2012 at 9:00 A.M. on 20 January. The three figures showed the same results as previous studies[2,10,28]. When the sea level rose, the inundation area expanded. Dunes and sandbars were almost submerged in the high-SLR scenario. Table 3 shows the water level results at three hydrological stations (Vamkenh, Anthuan, and Bentrai) in three main distributaries (Tieu River, Hamluong River, and Cochien River) of the Tien River. The mean water level rose 30 and 97-98 cm in the low- and high-SLR scenarios. The maximum water level increased by 44 and about 147 cm in the low- and high-SLR scenarios, but minimum water level values were about 9–11 and 27–33 cm, respectively.

Rising seawater and changes in upstream flow made the current in the study area more complex and led to noticeable current speed increases. In the low-SLR scenario, the Tieu, Dai, Cunghau, and Cochien Rivers had current speed increases of 4–6%, while the highest current speed increase of more than 7% occurred in the Hamluong River. However, in the high-SLR scenario, these values were larger and more dissimilar. The current speeds of the Tieu and Dai Rivers increased by 13 and 15%, while increases in the Hamluong and Cunghau Rivers were 19 and 20%, respectively. The values peaked at 21% in the Cochien River.

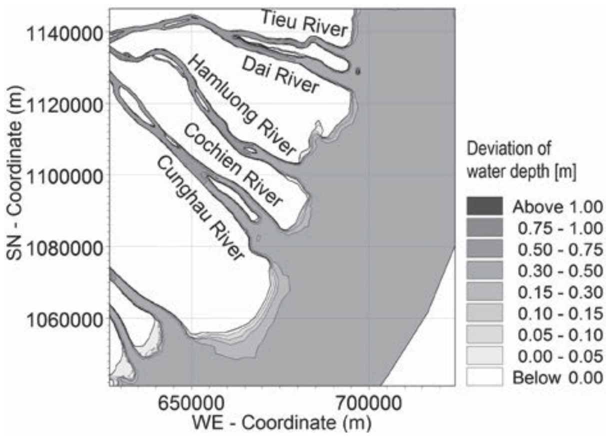

Fig. 9. The deviation in simulated water depth between the high-SLR scenario and the baseline at 18:00 (GMT +7) on January 20, 2012

According to the results obtained for the two SLR sce-

Table 3. Summary of surface level (m) results in the decade

Scenario	Items	Vamkenh (Tieu River)			Anthuan (Hamluong River)			Bentrai (Cochien River)		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Baseline	Surface level (1)	-2.58	1.86	-0.02	-2.60	1.90	-0.01	-2.95	1.97	-0.03
Low SLR	Surface level (2)	-2.47	2.30	0.28	-2.50	2.34	0.29	-2.85	2.42	0.27
	ΔH [(2)-(1)]	0.11	0.44	0.30	0.11	0.44	0.30	0.09	0.44	0.30
High SLR	Surface level (3)	-2.25	3.33	0.95	-2.28	3.36	0.96	-2.68	3.45	0.94
	ΔH [(3)-(1)]	0.33	1.47	0.97	0.33	1.46	0.98	0.27	1.48	0.98

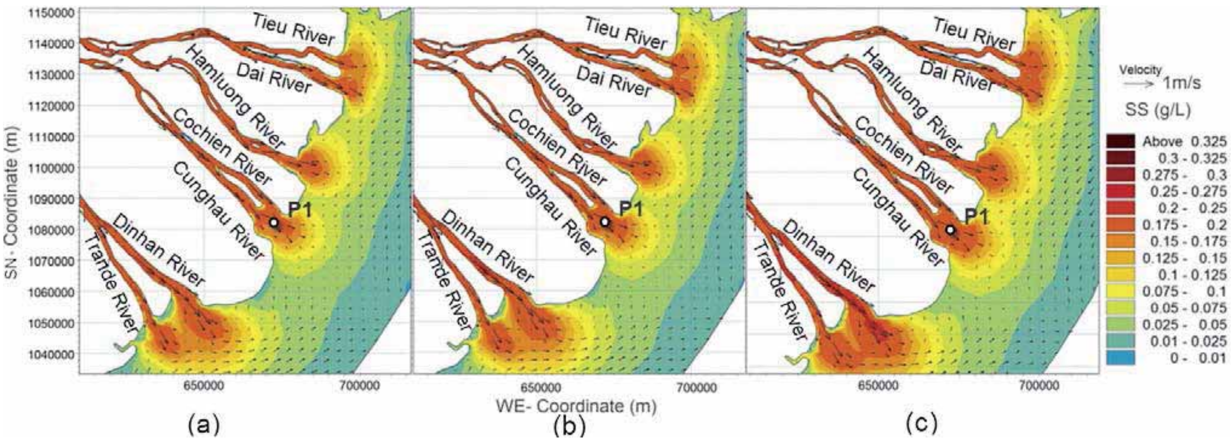

Fig. 10. Movement of suspended sediment at 15:00 (GMT +7) on September 6, 2010, (a) in the baseline; (b) in the low-SLR scenario; and (c) in the high-SLR scenario

narios, the simulated current was stronger and SS transport was higher than in the baseline. The strong currents increased erosion of the river bed, and the eroded sediment increased SS transport in the distal zone of the Tien River Estuaries. The SS was transported out of the river mouth. There was also an increase in SS transfer between the estuaries of the Mekong River in the coastal zone. This point is illustrated in Fig. 10. The SS in the Tien River as a result of the baseline (Fig. 10a) was about 0.2 g/L. Outside the Tien River mouths, the SS decreased below 0.075 g/L, while in the nearshore zone, the obtained SS was within the range 0.05 to 0.075 g/L. However, the SS reached only 0.025 g/L in the coastal region between the Tien River Estuaries and the Hau River Estuaries.

The result of the low-SLR scenario (Fig. 10b) indicated increased SS in the Tien River Estuary area, and the region in which SS exceeded 0.2 g/L was extended into the sea. Although there was an increase in sediment distribution in the coastal zone near the Tien River mouths, the SS did not change noticeably. In the high-SLR scenario (Fig. 10c), the SS was diffused significantly and its isoline was within the range 0.075–0.1 g/L, encompassing virtually the whole of the Tien River Estuary area. Remarkably, the obtained SS value exceeded 0.25 g/L in the area of the Tien River mouth. Furthermore, the region in which the SS value exceeded 0.2 g/L extended into the sea more than twice as much as the baseline. SS also increased in the area of the Hau River mouth with the maximum value exceeding 0.25 g/L. (See details in Table 4).

The river bed showed different erosion and deposition characteristics between flood and dry seasons. During the flood season, a high-velocity river current carried SS out of the river mouth and the sediment consolidated the sandbars, islets, and alluvial grounds of the Tien River Estuaries. Concurrently, this current was a major cause of erosion, rapidly eroding the river bed. During the dry season, the cold sea current dominated the Tien River Estuary area (see Fig. 11). In all SLR scenarios, the sea current accelerated and moved a portion of the sediment that had been deposited during the flood season southward. Furthermore, the strong cold current disrupted the weak foundation of the shoreline.

Figures 12, 13, and 14 illustrate further details of the erosion and deposition results for the Tien River Estuaries in the baseline, showing low- and high-SLR scenarios, respectively, for the decade from 2010 to 2020. Deposition and erosion processes of the SLR scenarios occurred to a far greater extent compared with those of the baseline. Long-term simulated results for the baseline of morphological

Table 4. Mean SS of baseline as compared to SLR scenarios

Simulation Case	Suspended sediment concentration	Hamluong (CR2)	Tieu-Dai (CR3)	Cochien-Cunghau (CR5)
Baseline	Mean SS (mg/l)	86.46	83.22	89.06
Low SLR	Mean SS (mg/l)	87.99	84.08	90.84
High SLR	Mean SS (mg/l)	95.01	90.91	95.17

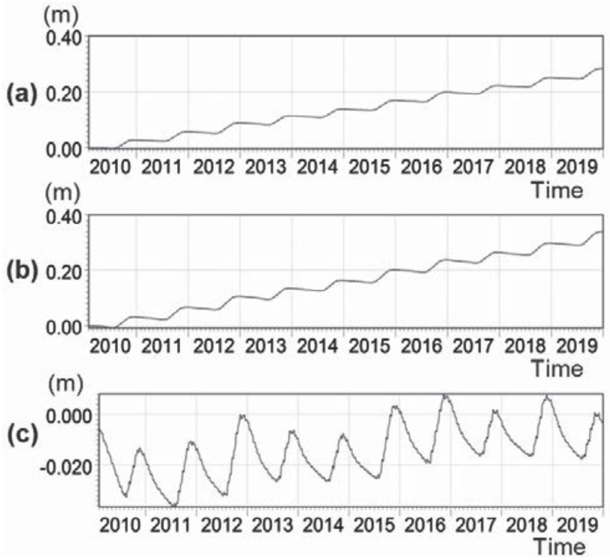

Fig. 11. Bed change at P1, shown in Fig 10, in different seasons in baseline (a); in the low-SLR scenario (b); in the high-SLR scenario (c)

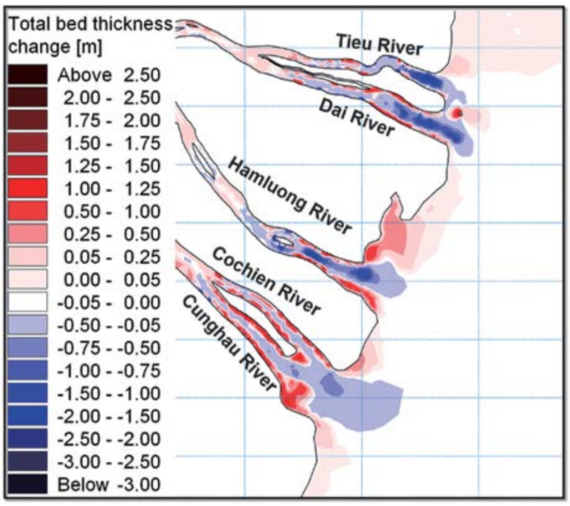

Fig. 12. Total change in bed thickness from 2010 to 2020 in the baseline

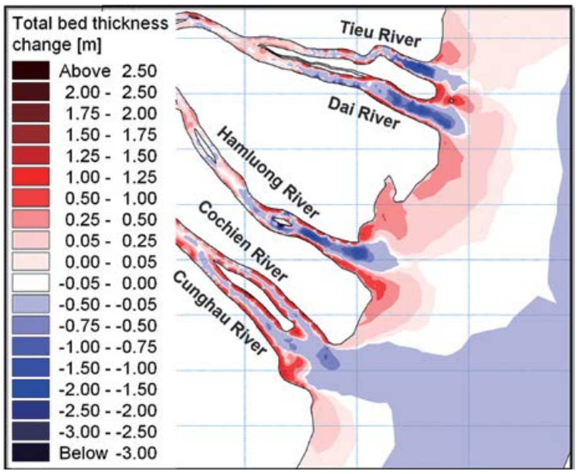

Fig. 13. Total change in bed thickness from 2010 to 2020 in the low-SLR scenario

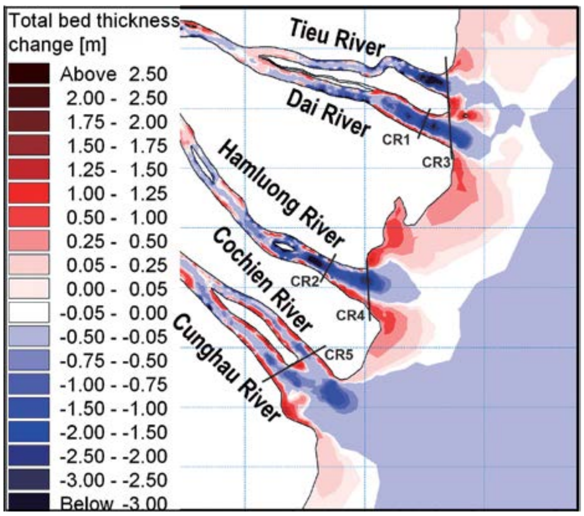

Fig. 14. Total change in bed thickness from 2010 to 2020 in the high-SLR scenario

evolution of the Tien River Estuaries showed that while the river bed was eroded, river banks were mostly consolidated. However, because of the strong cold sea current of the dry season, river shore degradation occurred sporadically where the foundation was weak. Sandbars were built and fortified during the flood season but later carved and moved slightly into the mainland (as illustrated in Fig. 15).

In the low-SLR scenario (Fig. 13), erosional processes intensified, causing Mekong River cross-sections to narrow and deepen. In the river, the depositional and erosional processes had trends equivalent to those in the baseline. River bed levels decreased and river banks aggraded significantly, although erosion alternated with deposition in some places. In the nearshore zone, SS settled easily while the sea bed was more eroded than in the baseline. In the high-SLR scenario (Fig. 14), although the bed of the Mekong River was

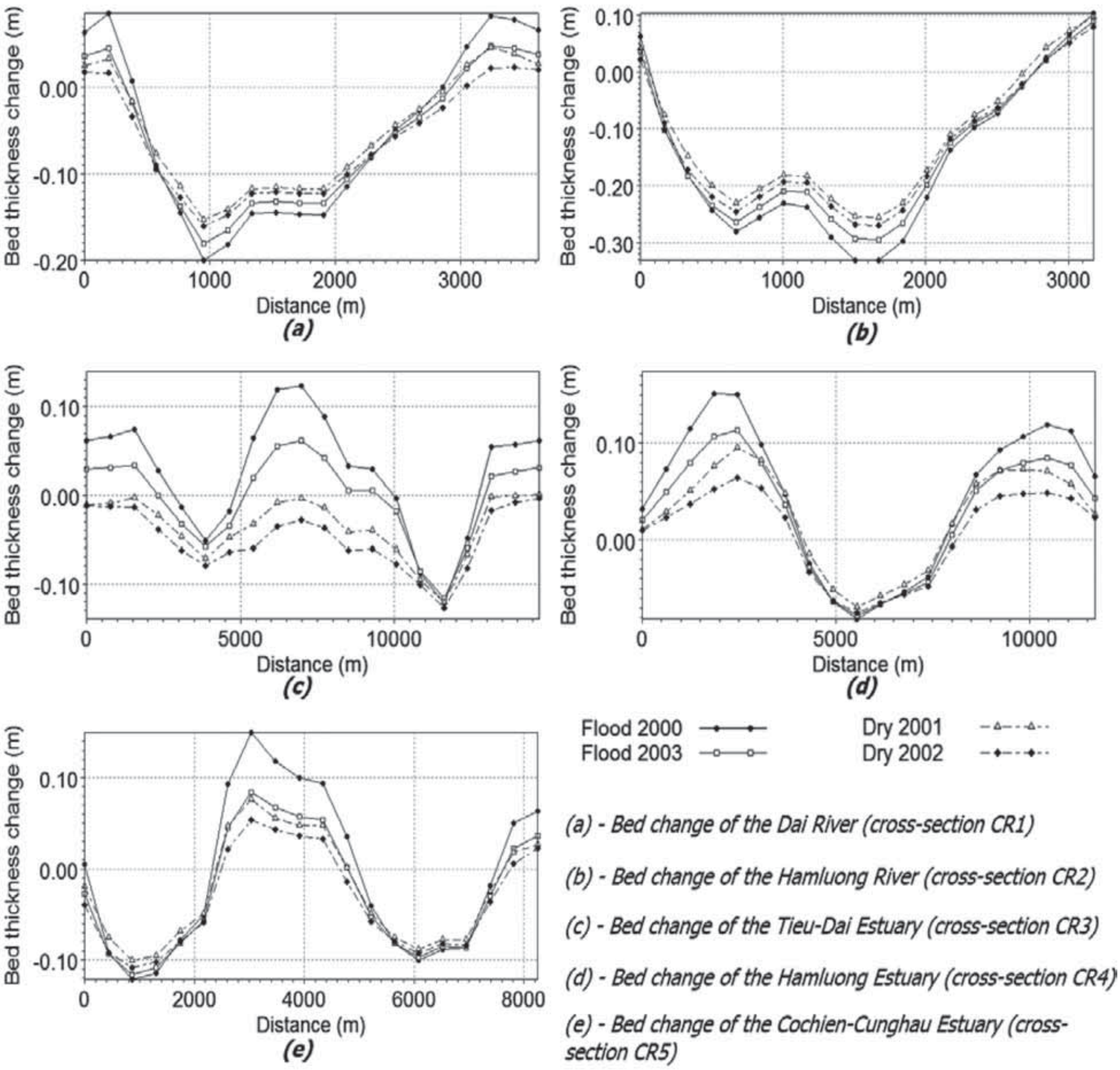

Fig. 15. Deposition and erosion having occurred at typical cross-sections in the Tien River Estuaries

strongly eroded, the shoreline of the Mekong River Estuaries was remarkably aggraded.

The results of bed thickness changes in the rivers and estuaries are shown in Fig. 16. Erosion in the high-SLR scenario was several times higher than in the baseline. The bed and sea bed were eroded by strong river and sea currents. In addition, although the river banks were virtually accreted, considerable erosion occurred at a few places along the Mekong River banks, such as along the Tieu, Dai, and Hamluong Rivers. Because tidal effects reach farther into the mainland with increasing sea level, associated erosion and deposition occurred not only at the river mouth area but also in the mainland. Tidal currents were most important among the erosion and deposition problems and tended to become more serious and complex (Fig. 13). These were the cause of the serious erosion in the Mekong River. The strong degradation of the bed caused the river banks to become unstable and prone to collapse easily at places where the river cross-section was narrow (Fig. 14).

2. Conclusions

Long-term simulation results of the baseline show that the factors contributing to the morphological evolution of the Tien River Estuaries are mainly natural. The influences of semidiurnal macro-tides, tidal asymmetry, river currents, sediment discharges, saline intrusion, and geological structure on the river's topography are considerable. The erosion of the Tien bed is very serious with a decrease of 0.5 m every year. The Tien River cross-section has narrowed and deepened due to erosion, while accretion of river banks and

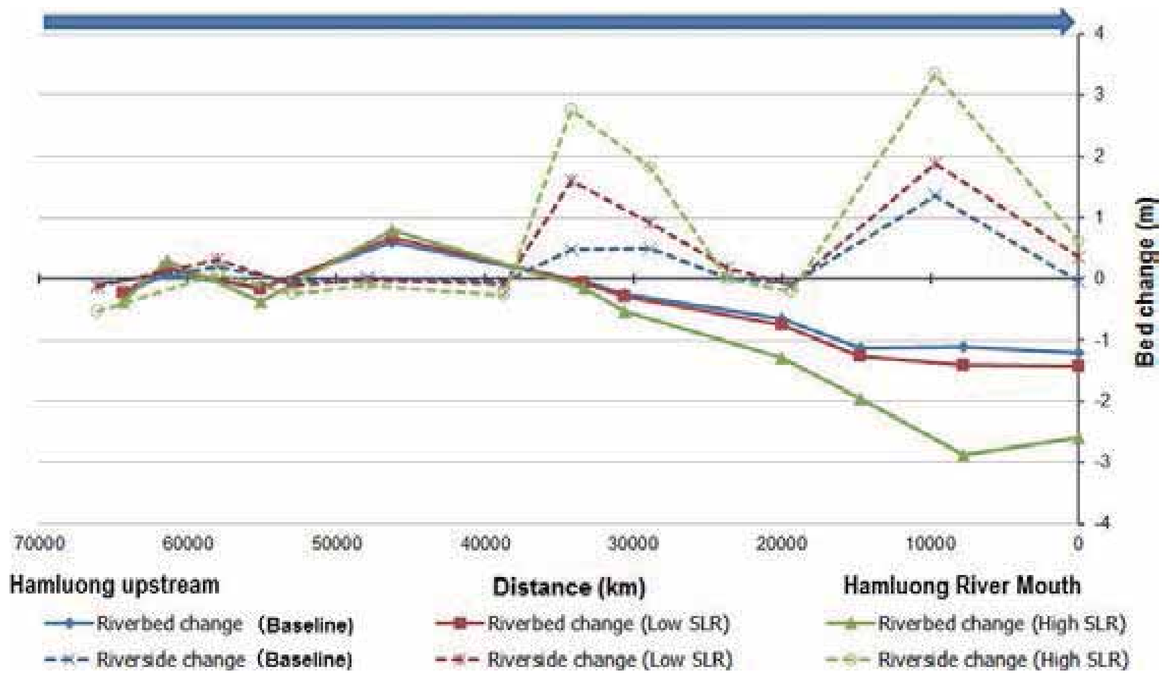

Fig. 16. Change in bed elevation along the Hamluong River

shorelines leads the Tien River to extend into the South China Sea. With high river discharge during flood season, suspended sediment is deposited in the distal zone, creating sand barriers and strengthening existing islets.

Influenced by SLR, current and sediment transport changed significantly in the Tien River Estuaries. The magnitude of the velocity values also increased slightly within the range 5–7% in the low-SLR scenario but increased considerably up to 21% in the Cochien and Cunghau Rivers in the high-SLR scenario. The strong current carried more SS out of the mouths of the Mekong River. In the two simulated SLR scenarios, SS was much higher in the estuarial area and led to consequent aggradation of the coastline in the Mekong River Estuaries, while the sea bed was degraded and the bathymetry of the coastal zone became a slope. However, the tidal influences differ between each estuary and distributary of the Mekong River. Tidal currents under the impact of the SLR scenarios largely intruded into the mainland leading to noticeable erosion and deposition in the Mekong River.

The results of this study suggest that, in the near future, after the sea level rises slightly (the low-SLR scenario), the morphological evolutions of the Tien River Estuaries will have the same trend as existing processes in the baseline, but erosion and deposition will intensify. However, a sea level increase of 1 m (high-SLR scenario) will significantly complicate the erosional and depositional processes. The influence of tidal activity will be extended further into the mainland and will cause deposition and erosion in both the river mouth and upstream river areas. River bed erosion will occur rapidly, and the bed level will rapidly decline, damaging river bank stability.

Acknowledgments

This research was conducted based on basic data of the key project KC.08.06.10; supported by the Vietnam Ministry of Natural Resources and Environment for designing SLR scenarios and formula functions. This research was partially supported by the FY 2012–2014 JSPS Core-to-Core Program (B. Asia–Africa Science Platforms) *Collaborative Project for Soil and Water Conservation in Southeast Asian Watersheds* and FY2011–2015 JSPS Grant-in-Aid for Scientific Research (B) (Project number 23380144).

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