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MODELING COASTAL AND ESTUARINE PROCESSES FOR COASTAL FLOOD MANAGEMENT AND EROSION PROTECTION AGAINST STORMS

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Abstract: *This paper presents a systematical approach to design an estuary by modeling coastal and estuarine processes for engineering application purposes of flood management and erosion protection against storms. A well-established coastal modeling system, CCHE2D-Coast, was used for simulating hydrodynamic and morphodynamic responses to short- and long-term hydrological conditions including river floods, extreme storms, and monsoon events. Several engineering design plans were comprehensively evaluated throughout based on the computed flood stages and erosion patterns in the estuary. The long-term morphodynamic simulations revealed the morphological stability of the design plans in terms of seasonal bed elevation changes. This paper demonstrates this systematical numerical simulation approach can facilitate the best engineering practices for coastal flood and erosion management under complex hydrological and geomorphic conditions driven by river floods, storms, and hurricanes/typhoons.*

Keywords: *Coastal/Estuarine Processes Modeling; Flood Management; Erosion Protection; Coastal/Estuary Design.*

INTRODUCTION

Coastal floods during hazardous storms and hurricanes/typhoons can be devastating by causing inundations, severe erosions, and even casualties in coastal and estuarine regions. Full assessment of the impacts of storms on coastal/riverine flooding, inundation, sediment transport, and shoreline erosion (including river degradation) is of vital importance in best engineering practices for flood management, erosion protection, and environmental impact assessment. It has been found that numerical modeling of coastal and estuarine processes driven by tide, storm wave, river flood, wind, and sediment transport provides a comprehensive assessment approach for engineers, managers, and decision makers to systematically evaluate the performance of engineering application projects for management of flood water stages and morphological changes.

In a short-term storm period or a long-term seasonal monsoon period, the complex and unsteady flows in rivers, coasts and estuaries generally induce significant temporal/spatial

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changes of bed elevations in river mouths, tidal inlets, and coastlines. Being able to compute detailed yet large-scale hydrodynamic and morphodynamic processes in time and space during the hydrological events, processes-based numerical simulation becomes an efficient and effective way to systematically access short and long-term impacts of storms, tides, and river floods. By means of short-term simulations of coastal and estuarine processes driven by storm events, most dangerous flood stages and maximum erosions/depositions can be computed to evaluate the security status of coasts and estuaries for protecting coastal communities from being inundated and eroded. On the other hand, long-term morphodynamic simulations for yearly-long storm and monsoon events can reveal the long-term morphological stability in the coastal and estuarine areas.

This paper presents an engineering application of CCHE2D-Coast, which is an integrated coastal and estuarine processes model (Ding et al 2006; Ding and Wang 2008) to simulate hydrodynamic and morphodynamic responses to various hydrological conditions by typhoons, waves, and storm-induced river floods at an estuary located at the west coast of Taiwan. This estuary, which is a medium-sized estuary, has equally important coastal and estuarine processes driven by tides, waves, river inflows, and winds. The sediments can be transported into the estuary by means of river flows, tidal currents, wave breaking across the surf zone, and typhoon/storm surges. The coastal and estuarine morphodynamic processes are of multiple-scale motions and therefore very complex.

In the study, dealing with six engineering conceptual plans for flood management and erosion protection in the estuary, the site-specifically validated CCHE2D-Coast was utilized to simulate hydrodynamic and morphodynamic responses to short- and long-term hydrological conditions. In the short-term hydrological condition containing a 100-year storm and a three-month-long monsoon, numerical results about the highest water stages and morphological changes in the estuary driven by these hypothetical storm and monsoon events enable engineers to identify the most desirable plan for flood prevention and erosion protection in the local area. In the long-term morphodynamic simulation under a hypothetical hydrological condition by repeated storm and monsoon events, morphodynamic stability over a long-term period in the selected design was investigated by evaluating seasonal morphological changes in the estuary. To do so, the systematical performance of the design plans for management of flood and sediment was evaluated by the numerical results of flood stages and erosions through both short- and long-term simulations. The assessment results in terms of numerical simulations facilitated the local engineers and managers to find the most cost-effective engineering design for coastal and estuarine defense against complex hydrological conditions such as storm waves, surges, high tides, and river floods, as well as erosion/deposition.

COASTAL AND ESTUARINE PROCESSES MODEL – CCHE2D-COAST

The coastal and estuarine processes model, CCHE2D-Coast, which was developed in the National Center for Computational Hydroscience and Engineering (NCCHE) at The University of Mississippi, has been used for simulations of waves, currents, sediment transport, and morphological changes in various coasts and estuaries for the purpose of coastal erosion protection and flood water management (Ding et al. 2006, Ding and Wang 2008). This model has systematically integrated three major submodels for simulating irregular wave deformations, tidal and wave-induced currents, sediment transport, and coastal morphological changes. As for the simulations of irregular waves, a multi-directional spectral wave-action balance equation with the diffraction effect terms was adopted in the wave spectral module. The hydrodynamic module is capable of simulating tidal currents, river flows, and nearshore currents induced by short waves (i.e. wind waves and storm waves). The morphodynamic module is to compute morphological changes due to sediment transport under the conditions of the combined waves and currents. The module can take into account various coastal structures, e.g., groins, offshore breakwaters, artificial headlands, jetties, artificial reefs (submerged dikes in coasts), as well as wetting/dry processes in computational domain.

This integrated modeling system has been extensively validated by simulating waves, wave-induced currents, and morphological changes in coastal applications in various laboratory and field scales. For example, the wave spectral model has been validated by simulating the refraction-diffraction effect as random waves propagate through a mounted shoal in a laboratory wave flume (Ding et al. 2004, Ding et al 2006). The hydrodynamic model was also validated by computed wave-induced longshore currents in a large-scale wave test facility (Hamilton and Ebersole 2001), and tidal currents in Hudson River, New York (Ding and Wang 2008). The validations of the morphodynamic model were achieved in simulating local morphological changes around a detached breakwater driven by waves (Ding et al 2006), and a long-term bed changes in Touchien Estuary, Taiwan, driven by river floods, storm waves, and tidal currents (Ding et al 2008). These validation cases have demonstrated that this integrated modeling system has various capabilities and reliable simulation accuracy to solve engineering application problems for the practical purposes of erosion protection and coastal flooding/inundation management.

AN ENGINEERING PROJECT FOR FLOOD MANAGEMENT AND EROSION PROTECTION

Engineering Project Site and Coastal Design

Hereafter, an engineering application of CCHE2D-Coast is presented to simulate coastal and estuarine processes in responses to short- and long-term hydrological conditions driven by storm waves, tides, and river floods at the Touchien estuary located at the west coast of Taiwan (Figure 1). Due to the rapid industrial and urban development, the local coastal communities with a dense population suffer from flooding and inundations, channel refilling in harbors, and property damages by shoreline erosions. They are in urgent need of a safe and attractive environment for flood protection and estuary/coastal stabilization. Thus, engineers have submitted six designs, which are sketched in Figure 2. Case 1, which is not shown in the figure, is considered as the status quo (or do-nothing) case. Most of these designs are based on theories and/or experience of the design engineers. Basically, they include: (a) building a 7-m high dike proposed to provide flood protection to the south bank with two optimal configuration variations. One is to follow the bank, and the other is a relatively straight line, so that the area in the lee of the dike can be used for reclamation; (b) deepening a channel north of the Jiugang Island by dredging; and (c) removing a sand bar (Beiliao Island) and constructing a jetty to separate the flows for the two rivers. As one can see from Figure 2, each design was a combination of some of these three basic aspects, which were noted below the schematics of each case. Apparently, without an objective and scientific measuring tool or technique, it was difficult to make the final selection.

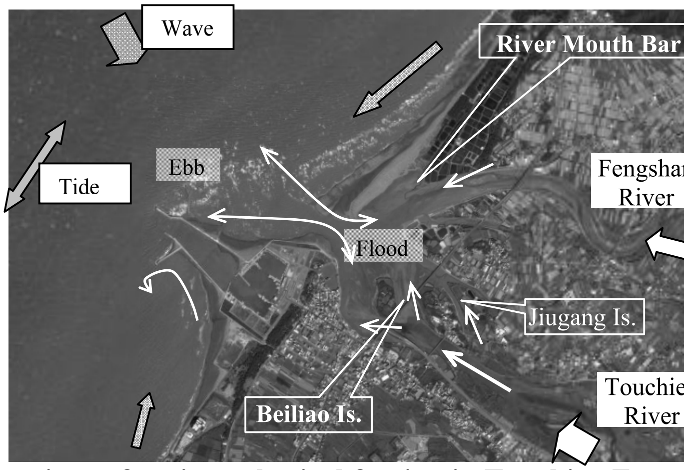


Figure 1 Interactions of various physical forcing in Touchien Estuary: the arrows indicate flow directions driven by wave, tide, and river inflow.

The N ational Center for Co mputational Hy droscience an d Engin eering (N CCHE) at th e University of Mississippi was a sked to apply the latest co mputational simulation technology to simulate the perfor mances of all six de signs, both short- and long-term, subject to selected storm/typhoon and monsoon events fro m the lo cal histori cal data, so t hat th e "b est" desig n can be determined by comparing the over-all performances of the six designs. An integrated coastal and estuarine modeling sy stem, C CHE2D-Coast, is therefore, s elected to assess th e performance of the six deign cases a nd one s tatus-quo cas e (Case 1). At first, utilizi ng a portion of the field d ata collected, the model parameters of basic modules and the integrated package were carefully calibrated. This is an very important step, because it brings the locally unique and site-specif ic characteristics (both geophysical and hy drological) into th e simulation m odels. Records fro m past hydrological ev ents (e .g. floods, storms, typhoons, etc.) and the response of the site were used to validate CCHE2D-Coast or "Hind-Casting" the model's cap ability of re producing the fiel d processes real istically. One may refer to D ing et al (2008) for t he detail s on th e site-specific model validat ion. The results of t he v alidation tests would be used also to enhance our understanding of the coastal and estu arine flow and sediment tr ansport pro cesses. Som e of t he si mulated field pro cesses, du e to various hydrological forcings, including water stages and overtopping along the banks of the estuary, river bed and bank to e erosions, sand bar growth and br eaching, etc ., have not on ly further enhanced o ur k nowledge of the estua rine resp onses to different hy drological forcings, bu t also strengthened our confidence to apply the CCHE2D-Coast to predict the performances of new designs under a variety of hydrological forcings.

A non-orthogonal mesh covering the Touchien River and the Fengshan River, the estuary, a fishery harbor, and a few kil ometer-long ad jacent coasts fac ing to Taiwan Strait was generated for testing the six designs (please see Figure 2 in Ding et al (2008) for the details of the mesh). This mesh was modified more or less according to the installed structures in each case of th e design. Th e require d boundary conditions are: (1) at t he inlets of two rivers, hydrographs were generated by a one-dimensional model of the National Chaio Tung University in Taiwan; and (2) at the offshore boundaries, the incident wave, tidal elevation, and currents were provided by the National Cheng Kung University in Taiwan. Both offshore boundary hydrographs and those at river inlets are time series with different scales and being varied with hydrological events. As a result, the flow fields inside the estuary, especially near the river mouth are rather complicated.

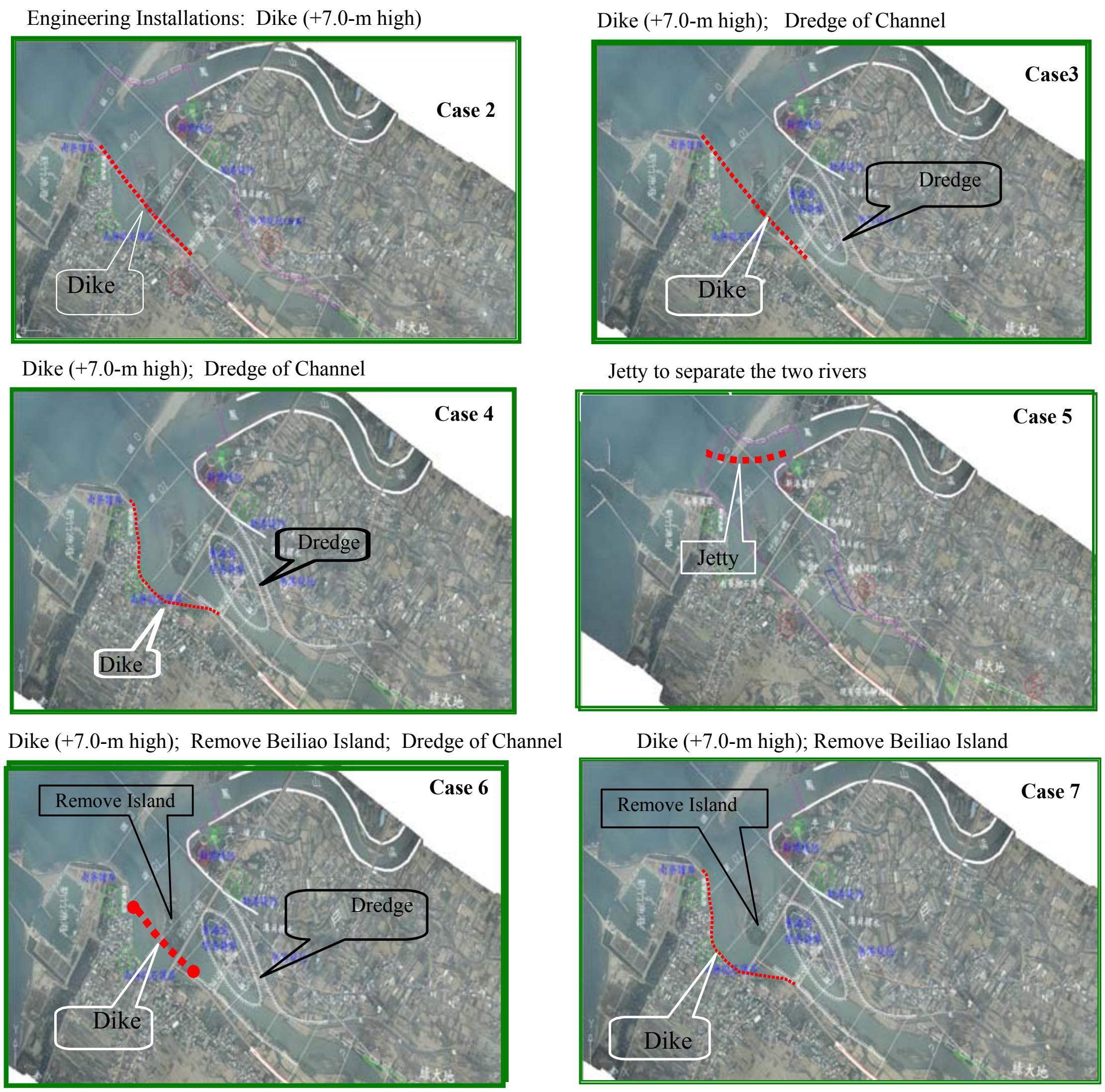


Figure 2 Engineering Plans for Flood and Erosion Protection in Touchien Estuary

Because there is a significant difference in sediment transport in coast and river, a total load sediment transport formulation which takes into account transition effect of sediment transport from river into coast was proposed and used to calculate sediment fluxes and morphodynamic changes. The coastal morphodynamic model was validated by comparing the computed morphological changes with the measured bed elevation changes. The measurement area in 2006 covered the Touchien estuarine area and the tidal reaches of the two rivers. From the validation results (Ding et al. 2008) the long-term morphodynamic simulations and migration of offshore bars, morphological changes in the estuarine area and upstream river reaches observed at the site were in agreement with those observations.

Short-Term Simulations for Evaluation of the Designs

The simulation of the performance of each design case should be done in three steps: (1) Using the hydrographs of a selected single event such as an extreme flood, a typhoon, or a monsoon season; (2) using a combination of a few events mentioned above over a relatively short period, such as a year or 6 months; and (3) using a combination of a representative hydrological event of a long or longer period such as 3 to 10 years. The last step is intended primarily for testing the design's effectiveness on sustainability from the long-term point of view. The practical and cost-effective approach to predict the long-term outcome of morphological changes of a conceptual design is not to run the simulation model in real time over the specified period, but rather a carefully designed synthetic hydrograph over a short period to produce an equivalent outcome. This is especially advisable if the simulated outcomes of different designs are used for comparison purposes.

In the present study, the synthetic hydrographs are combinations of several hydrological events which occurred in the past years such as typhoons, storm surges, floods, monsoons, and normal tides and river flows (Figure 3). The reason to use the past hydrological events is the availability of recorded data, both the hydrological forcing conditions and responses of the estuary. In order to raise the level of test criteria, one may want to choose worse hydrological events as elements to construct the synthetic hydrographs. As shown in Figure 3, for an example, one set of the hydrographs contains a short-period storm-induced "100 year" flood and a three-month-long monsoon season. It was used as a short-term hydrological condition for all the design tests. Similar hydrographs can be also synthesized by combining extreme typhoons, floods, monsoons, and base flows as needed. Most of the hydrological events utilized were from past records.

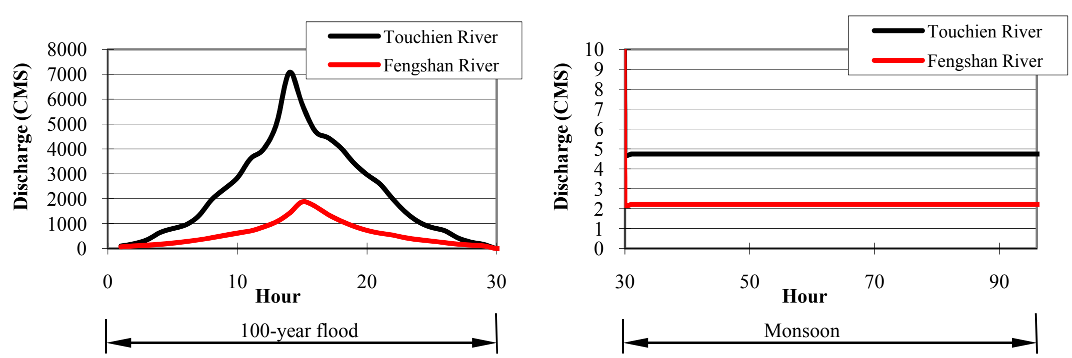


Figure 3 Hypothetical hydrographs to represent a 100 year flood and a 3-month monsoon

By applying this short-term hydrological event to evaluate all the design plans, CCHE2D-Coast produced the hydrodynamic and morphodynamic responses to the 100-year storm and the 3-month-long monsoon. For Case 1, it was seen from Figure 4, that the simulated highest water stages during the "100-year" flood period exceeded the proposed dike height (7-m) at several locations. This finding indicated at least that just by building a 7-m dike alone would not provide the flood protection objective set for the project. It explained why most of the conceptual designs suggested additional engineering measures to supplement the construction of such a dike.

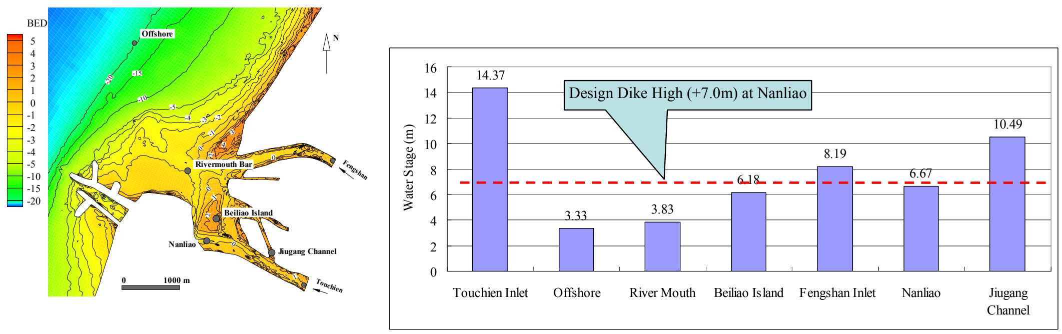


Figure 4 Highest water stages at seven monitoring stations in the 100-year storm (Case 1)

After a comprehensive evaluation of all 6 designs' effectiveness or performance subjected to the same synthetic (or hypothetic) hydrographs, the resulting highest water stages at the most important location (i.e. Nanliao station) in the estuary are plotted in Figure 5. It was found that the design Case 7 (i.e., to build a 7-m dike together with the removal of the Beiliao Island) would result in having the lowest water stage at the Nanliao location in the estuary, where the highest water stage would be reduced to 5.8-m (less than the 7-m dike high).

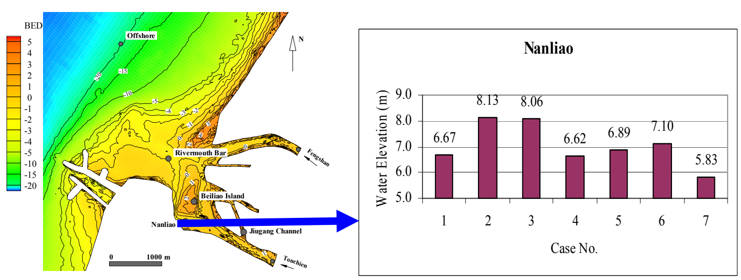


Figure 5 Comparisons of highest water stages of the six cases at Nanliao Station

Long-Term Morphological Change Predictions

There was one more test to conduct before the most effective design is selected for construction: that was the effectiveness of the design to sustain the long-term stability of the Touchien Estuary and the coastal line nearby. For this purpose, another set of hydrographs was constructed or synthesized. It was a combination of three typhoons (the Haitang, Matsa, and Talim happened in the summer of 2005 (Ding et al. 2008)) and one 3-month long monsoon season, as shown in Figure 6. In order to determine the long-term morphodynamic evolutions on the bed and banks of the estuary as well as the coastal zone nearby due to repeated hydrological events, it was decided to run the simulations repeatedly using the same hydrographs with new morphological conditions after each cycle, rather than reconstruct hypothetic hydrographs for each year. The morphodynamic responses of Case 7 for the long-term hydrological events are presented in Figure 7. The simulated morphological changes after the first storm is given in Figure 7a, which shows erosions occurred at the river mouth and depositions in the area of the removed island. One sees also sand bars have been developed in the vicinity of the tip of jetties of the harbor. Figure 7b shows the simulated bed changes after the first monsoon, which displayed the offshore sand bar migrations and scouring near the tip of jetties. It is also seen that sediment depositions are in several locations in the estuary and at the river mouth. During the following storms and monsoons, similar morphological activities are shown in Figure 7c and 9d. From the results of long-term simulations, the trend of overall bed changes indicates that the bed and bank erosions and sedimentations, the sand bar formation, breaching and migration, have exhibited a periodic behavior and the trend of net morphodynamic changes of the bed and bank elevations were either increasing or decreasing asymptotically depending on the mitigating engineering project designs.

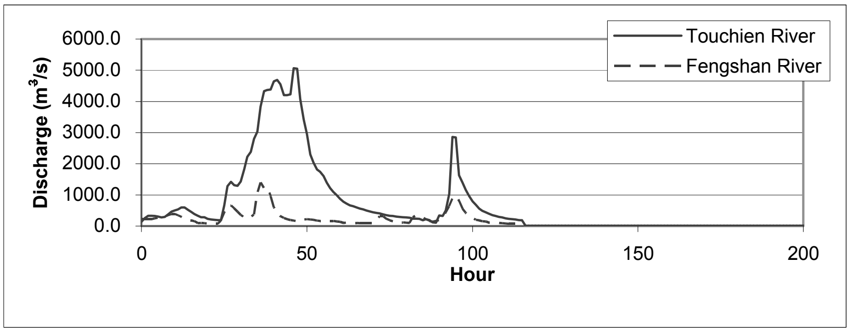
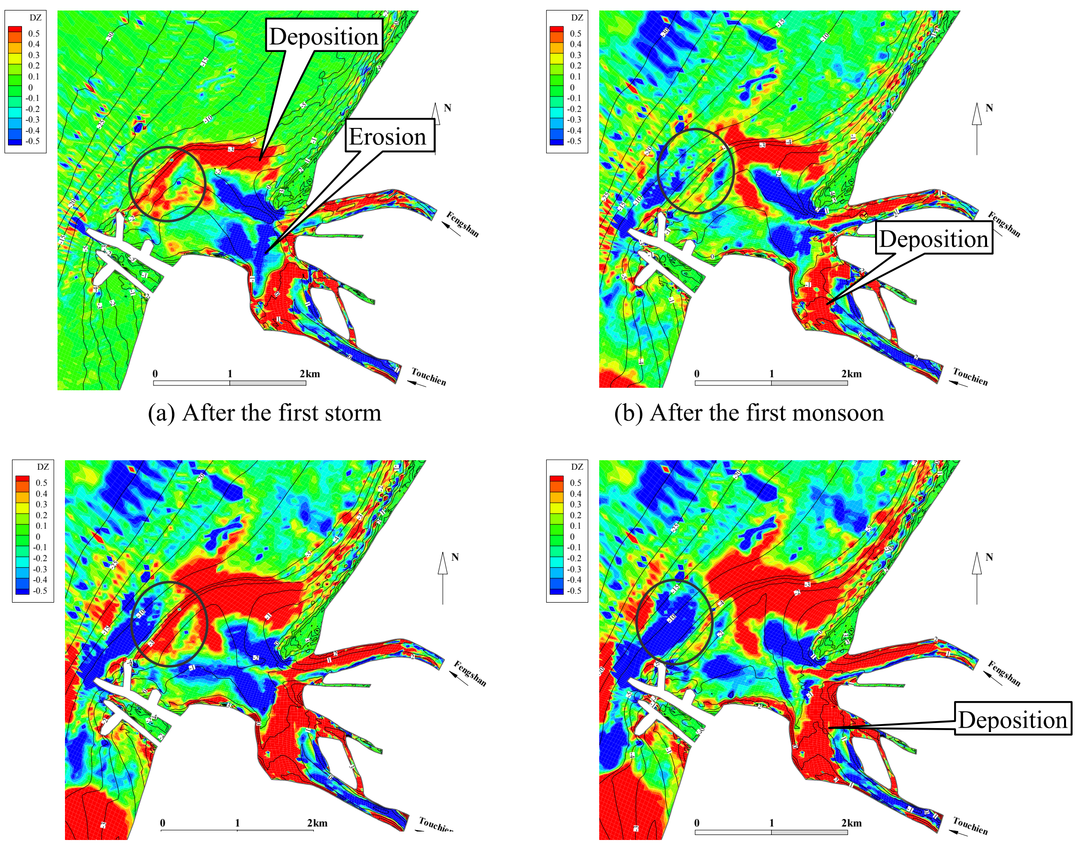


Figure 6 Two hydrographs for the two river inlets in the storms period



(a) After the first storm (b) After the first monsoon

(c) After the third storm (d) After the third monsoon

Figure 7 Computed seasonal bed changes and bed elevations (Unit: m)

From the bed elevation changes at Beiliao station as shown in Figure 8 , It is found that the variations of the bed elevations in the first storm season are fastest in the whole period; then the changes of bed elevations in the following storms tend to be less and less, and eventually stable. The seasonal changes of bed elevations show the following important characteristics: (1) The storm always creates more significant bed changes than the monsoon; (2) The monsoon plays an important role of a recovery forcing to compensate the bed changes by the storm does; (3) The variations of the bed changes tend to be less and less along with the increase of time; (4) The bathymetry in the estuary responding to the hypothetical/periodical events (boundary conditions) can reach a dynamic equilibrium state; (5) After Beiliao Island is removed, sands from upstream will deposit in the areas of the Beiliao Island in almost all the seasons. Bed elevation at the Beiliao will be lift up to 1.30m after the three storm-monsoon-cycles simulations.

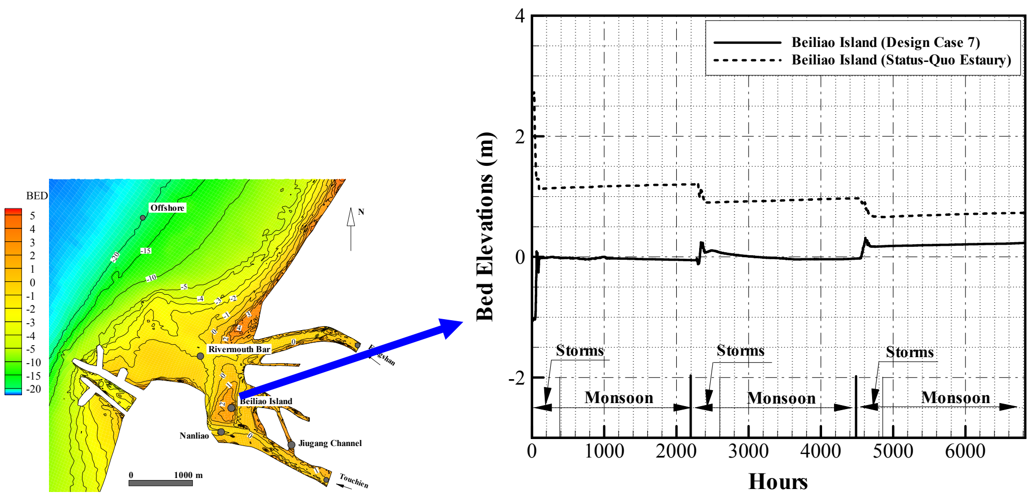


Figure 8 Long-term overall bed elevation changes at Beiliao Island in the estuary

CONCLUSIONS

This paper presents a systematical approach to design coasts and estuaries by means of an integrated coastal and estuarine process modeling technology, for coastal flood management and erosion protection against storms and hurricanes or typhoons. An engineering application project is demonstrated to find the most effective design plan for flood prevention and erosion protection in an estuary by systematically simulating waves, currents, sediment transport, and morphological change. In the project, dealing with six engineering conceptual plans and a status-quo case, the site-specifically validated CCHE2D-Coast was utilized to simulate hydrodynamic and morphodynamic responses to both short- and long-term hydrological conditions. In the short-term hydrological condition containing a hypothetical 100-year storm and a three-month-long monsoon, numerical results about the highest water stages, flood flow propagation, and morphological changes in the estuary driven by the hypothetical storm and monsoon events enabled engineers to identify the most desirable plan (i.e. Case 7) for flood prevention and erosion protection. In the long-term morphodynamic simulation under a hypothetical hydrological condition by repeated extreme storm and monsoon events, morphodynamic stability over a long-term period in the selected design (Case 7) was investigated by evaluating seasonal morphological changes in the estuary. To do so, the performance of the design plans for management of flood and sediment was systematically evaluated through both short- and long-term simulations. It is demonstrated that the numerical modeling of coastal and estuarine processes by CCHE2D-Coast can facilitate engineers, researchers, and coastal planners to find the most cost-effective engineering design for coastal and estuarine defense against complex hydrological conditions such as storm waves, surges, high tides, and river floods, as well as sediment erosion/deposition.

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