Hydrodynamic Condition Modeling along the North-Central Coast of Vietnam

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***Abstract*—An extremely dynamic morphology of the estuary is observed in the coastal regions of Vietnam under the governing processes of tides, waves, and river system flows. The primary target of this paper is to provide insight into the governing processes and morphological behavior of the Nhat Le estuary, located in the north-central coast of Vietnam. Based on measured data from field surveys and satellite images combined with numerical model simulations of MIKE and Delft3D, the influences of seasonal river flow, tides, and wave dynamics on the sediment transport and morphological changes are fully examined. The study showed that freshwater flow in the flood season plays a central role in cutting off the southern sandspit, maintain and shaping the main channel. The prevailing waves in winter and summer induce longshore drift and sediment transport in the southeast to northwest direction. In the low flow season, this longshore sediment transport is dominant, causing sediment to deposit on the southern side of the ebb tidal delta and elongating the southern sandspit which narrows the estuary entrance and reorients the main channel.**

Keywords-hydrodynamics; morphology; Delft3D; Nhat Le estuary; MIKE

I. INTRODUCTION

Coastal and estuarial morphological features highly depend on the combined influence and interplay of river flows, waves, tides, and currents. Additionally, meteorological phenomena significantly affect the hydrodynamic and morphodynamic processes of estuarial and coastal zones [1]. Especially in the tropics, the effects of atmospheric circulations on a synoptic scale on the precipitation regime and changes in temperature are carefully monitored [2-3]. The behavior of hydrologic processes is analyzed by hydrological models [4]. Generally, these studies illustrate changes in river flows and evolutions of estuarial or oceanic features dominated by the effects of atmospheric circulations. The effects of dam construction on the morphology are investigated in [5]. Authors in [6] used the Deflt3D system [5] to study the fluvial erosion and to investigate the temporal evolutions of hydrodynamic processes. This system is widely applied in researches in hydrodynamics, sediment transport and wave modeling [8-12]. Interaction of wave-current and tidal depth changes are considered in Katama Bay using combined models of Deflt3D-FLOW and SWAN. These studies indicated a good reproduction of waves and currents. These studies mostly emphasize on the regions dominated by physical processes at a large scale. For many projects dealing with water resources and hydrodynamics, MIKE system [13] is applied [14-17]. The uncertainty strongly depends on a large range of data requirements and parameter values [18]. In other words, there is a need to further investigate the performance of MIKE for the estuary and coastal areas in the tropics like Vietnam where the dynamics are very unstable. In the coastal zones of Vietnam, human activities and natural environment changes lead to imbalance in the coastal processes, changes in dynamical action, and sediment transfer. So far, only a small number of studies have been conducted in this topic [19-20].

The Nhat Le estuary is selected as a study area, along the north-central coast of Vietnam. It is located in Quang Binh province as shown in Figure 1. It connects a drainage basin of 2647km^2 to the Gulf of Tonkin. Under the governance of wave and river hydrodynamics in a tropical monsoon region, the morphology of the estuary and the adjacent coast are very dynamic and unstable. During the last ten years, the development of the southern sandspit posed difficulties for navigation, especially for the fishing boats entering the shelter areas during typhoons or rough sea conditions. Since 1977, the northern and southern coasts have been eroded by the alternate attacks of the monsoon waves. Many research and dredging projects have been invested and several coastal structures have been built to stabilize the estuary, but the problems remain, due

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to the fact that the main governing processes and the actual mechanism of the estuary's morphological instabilities are still not clearly understood. Therefore, the goad of this study is to comprehend the changes in bed-sea topography and the causes of estuary evolution, while additionally providing more insight into the main governing processes and the behavior of the morphology at the estuary based on measured data and numerical modeling of hydrodynamics, sediment transport, and morphological changes at the estuary.

Fig. 1. Study area (screenshot from Google Earth, map data: Esri, Digital Globe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)

II. THE STUDY AREA

The Nhat Le River is 85km long, origins from the Truong Son Cordillera with two major tributaries, Dai Giang and Kien Giang, and discharges into the sea at Dong Hoi city. Near the estuary the river has a width of about 400 to 500m, an average depth of 2 to 4.5m and a maximum depth of 7m. The river flow regime is strongly governed by the tropical monsoon climate regime with the two distinguish flood and dry seasons. The flood season lasts from September to December when the northeast monsoon winds carry moisture from the sea and cause considerable rainfall and river floods. Also, torrential rain may occur from July to October due to severe typhoons coming from the Western Pacific basin. The flood season only lasts four months but produces 76% of the annual flow. The mean annual rainfall is about 2500mm. The dry season is characterized by a dry and hot climate due to the sheltering of the Truong Son Cordillera from the southwest monsoon winds.

The tidal regime in this area is semi-diurnal with a spring tidal range of 1.2-1.6m. Due to the micro tidal regime, the tidal currents are also weak. The observed tidal currents along the coast are smaller than 0.5m/s. The wave climate strongly reflects the monsoon system. In the northeast monsoon season the prevailing wave direction is from Northeast, the average wave height is 0.8-0.9m but the highest winter wave height can be 4.0-4.5m. In the summer, the dominant wave directions are Southwest and Southeast with an average wave height of 0.6-0.7m while the highest wave height can reach 3.5–4.0m. During major storms wave height may exceed heights of 6m.

III. MATERIALS AND METHODOLOGY

A. Materials

Instruments were used and installed at measurement stations. Typically, the Trimble R8s is used to create a topography on land [21]. JMCF-2000 and Odom Hydrotrac II are used to create a topography of the seabed [22]. The primary instrument used for wave data collection was the Nortek Acoustic Wave and Current Profiler (AWAC) [23]. Field data at the Nhat Le estuary have been measured intensively by the authors themselves for projects of the Institute of Geography (e.g. project with the code VAST 06.03/15-16) during the period from 2005 to 2016. The data include bottom topography, waves, tidal water level, river discharge, and sediment grain sizes. Within this project, Dong Hoi hydrologic station is newly installed to measure tidal water level and discharge. The data include bottom topography, waves, tidal water level, river discharge, and sediment grain sizes. Figure 2 shows the locations of stations including the Dong-Hoi hydrological station and AWAC deployments to measure waves.

B. Numerical Modeling: Set-up and Boundary Conditions

The MIKE is an implicit finite difference model for one dimensional unsteady flow computation and can be applied to simulate surface runoff, flow, sediment transport, estuaries, water quality or floodplains [13]. For this study, MIKE 11HD package was applied [13]. The upstream boundary conditions include river flow discharge computed for 8 tributaries using rainfall-runoff model (i.e. Nedbor - Astromnings - Model (NAM)) [24] coupled with MIKE 11 [25]. The NAM model is used as a module of MIKE 11 under the name of MIKE-NAM. The output of NAM (i.e. discharge) is used as upper boundary condition at 8 the tributaries for MIKE 11HD to compute the hydraulic boundaries. The upper boundary locations are shown in Figure 2. This model was originally developed by the Department of Hydrodynamics and Water Resources at the Technical University of Denmark [26]. It is a conceptual model, describing the physical characteristics of the basin, on the basis of which it calculates rainfall flows. The NAM is the conceptual hydrological model. Its parameters and variables present the mean values for the entire basin. The input data for NAM include the time series data of rainfall at Kien Giang hydrologic station (17°00'40.89"N, 106°44'09.94"E), time series of daily mean air temperature, wind speed, relative humidity, and solar radiation at Dong Hoi (Meteo) (17°28'19.83"N, 106°37'27.32"E) to simulate daily evaportranspiration, and flow discharge for the catchments.

The process-based numerical model system Delft3D [7] primarily designed with a focus on applications of water flow and quality, was applied in this study. The ocean forcings (i.e. tidal, wave actions, and sediment transport) were simulated using the Delft3D model, namely a couple of Delft3D-FLOW and Delft3D-WAVE using SWAN [7, 27-28] were applied to take into account the influences of tides, wave forcing, and river discharges. The FLOW model is a hydrodynamic component of Delft3D with a three dimensional hydrodynamic and transport simulation program. It is applied to solve the depth-averaged non-linear shallow water equations for non-steady flows. Simulations of hydrodynamic, sediment transport changes were conducted. The WAVE model is also a component of Delft3D with two available modules of HISWA [29] and SWAN [27] as the second and third generation wave model, respectively. In this study, SWAN model was applied for wave propagation and transformation in near-shore.

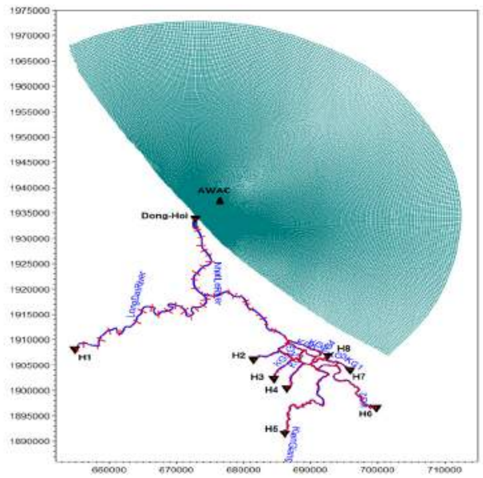

Fig. 2. Computational domain and grid

The modules of RGFGRID and QUICKIN combined within the Delft3D system were used to create smooth, orthogonal curvilinear grids and interpolate the topographic data. Figure 2 shows the model domain, computational grid, bathymetry at the estuary and locations of upstream flow boundaries and observation stations. The computational grid for the Nhat Le estuary and its rivers and adjacent continental shelf consists of 512×329 nodes. Fine-grid resolution was used locally and coarse resolution was used away from the regions of interest. The maximum grid size at the offshore open boundary is about 300m. The depth is extended to -5m and -52m for the near-shore and offshore areas respectively. The grid areas are enlarged from about 3km up to about 40km for the boundary of near-shore and offshore far from the coastline respectively. Grid cells in the main estuary channels are 15m in length, while grid cells in outer are up to 300m in length. The bathymetry for the fine grid mesh is taken from survey at 30m resolution in the Nhat Le estuary area and 500m resolution for offshore areas. The seaward open boundary forcings were assumed to be astronomical tides. Based on the global ocean tide model TPXO 8.0 [30], ten tidal constituents of Q_1, O_1, P_1, K_1, M_2, S_2, K_2, N_2, Mf, Mm were found to be dominant in the area and were used as the open boundary conditions of the model. Note that the boundary conditions of wave model are deep-water wave parameters (i.e. significant wave height, peak wave period, mean wave direction) from WAVEWATCH III model [28]. For simulations of sediment transport, the parameters automatically adopted from [8-9, 32-33] were used.

IV. RESULTS AND DISCUSSION

A. Results

At first the model performance of MIKE and Delft3D system needs to be calibrated and validated. In the process of calibration, model parameters were modified to reduce the error between the simulated and observed discharges. The model parameters found during model calibration were kept in the process of validation. The measured flow data at Kien-Giang station were used to validate the rainfall-runoff and river flow model. Figure 3 shows the discharge simulations of MIKE system for calibration and validation during the flood seasons of 2015 and 2016. It is observed that the difference between simulation and observation discharge at Kien Giang is negligible with Nash-Sutcliffe indices [26] of 0.89 (in 2015) and 0.98 (in 2016). It is significantly remarkable to provide well-fitted results of models against the measured data as shown in Figure 3 at Kien-Giang station. The model calibration and validation showed that the timing of the peaks was captured well, but the model slightly underestimated the discharge value in November 2015 for calibration. The parameters of overland flow runoff coefficient (CQOF) and time constants for routing overland flow (CK12) are most sensitive to the simulation results of discharge, followed by the maximum water content in root zone storage (Lmax) and root zone threshold value for overland flow (TOF) parameters. These parameters are defined on the basis of statistical performance indices (i.e. coefficient of determination).

(a)

(b)

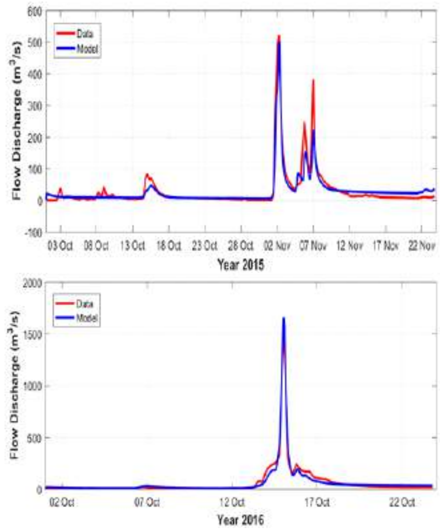

Fig. 3. Comparison between modeled and observed flow discharges at Kien-Giang station for the flood seasons in (a) 2015 and (b) 2016

The hydrodynamic model was calibrated for the period from 16 May to 20 May 2015 using the collected data at the AWAC station in the estuary. Model validation is firstly performed using the water level, depth averaged current, and wave measurements at the AWAC station. Figures 4-5 present a comparison between model predictions and measurements for water surface levels and depth averaged flow currents at AWAC station. The Nash-Sutcliffe indices for the efficiencies of the model versus data for water surface elevation, x- and y-components of flow velocity are 0.96, 0.76 and 0.63 respectively indicating a good agreement between the model and the data. The model output is mostly influenced by the water level and discharge at the model boundaries and is especially sensitive to winds. Besides water surface elevation and depth averaged flow currents, the comparison of wave parameters including significant wave height, wave period, and wave direction between model and data also provides reasonable agreement (Figure 6).The satellite images and field survey data were used to validate the simulations of the sediment transport.

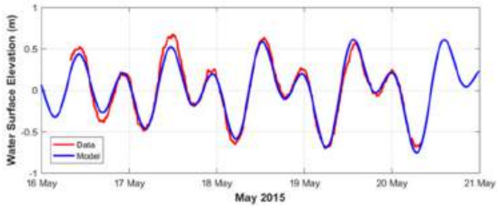

Fig. 4. Modeled (blue) and measured (red) water level at AWAC station

(a)

(b)

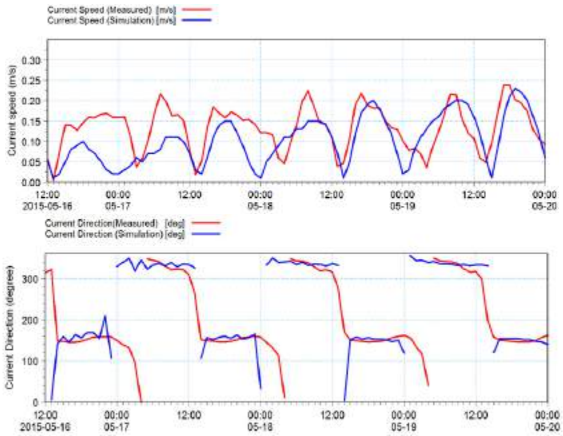

Fig. 5. Comparison between modeled (blue) and measured (red) flow velocities for (a) x- and (b) y- components at AWAC station

(a)

(b)

(c)

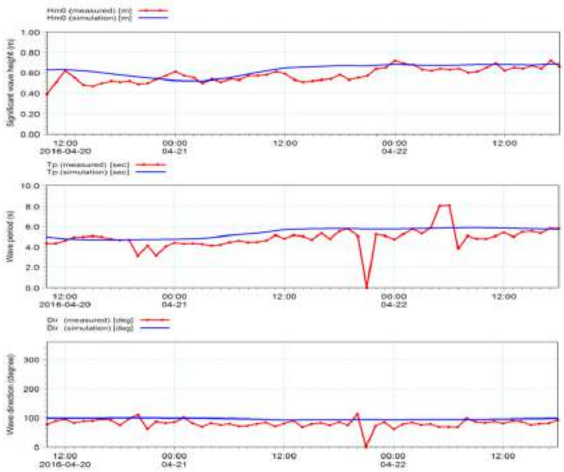

Fig. 6. Model prediction and measured data comparison for (a) significant wave height, (b) wave period, and (c) wave direction at AWAC station

B. Discussion

Based on the calibrated model, hydrodynamics and morphodynamics of the Nhat Le estuary were simulated and analyzed to investigate the influences of different governing processes such as tides, waves and river flows. Firstly, a simulation of fresh water inflow and tides-only forcing was carried out. Then a fully hydrodynamic model of all forcing (fresh water inflow, tides, winds and waves) was simulated. Two simulation periods, May 2015 and September 2015, represented the different conditions in summer and winter respectively.

1) Wave Characteristics

The model results of wave parameters were extracted at four different locations (P1 to P4) surrounding the entrance (Figure 7(a)). Wave roses for the period of 2015-2016 are plotted for these locations in Figure 7(b). The purpose of this is to clarify the role of winds in affecting the wave characteristics. It is observed that the deep-water waves are prevailing from the East and North-Northeast directions. When the waves are approaching the estuary, the dominant wave directions are East and Northeast due to wave refraction. As the Northeast waves are mostly normal to the coastline, the wave action would contribute mainly on the cross-shore sediment transport but not the long-shore sediment transport. Therefore, the dominant Eastern waves could be the major source in inducing long-shore sediment transport in the estuary. Due to the dominant Eastern wave actions, the net long-shore sediment transport is directed in the Southeast-Northwest which elongates the southern sandspit and forces the main channel to head North.

(a)

(b)

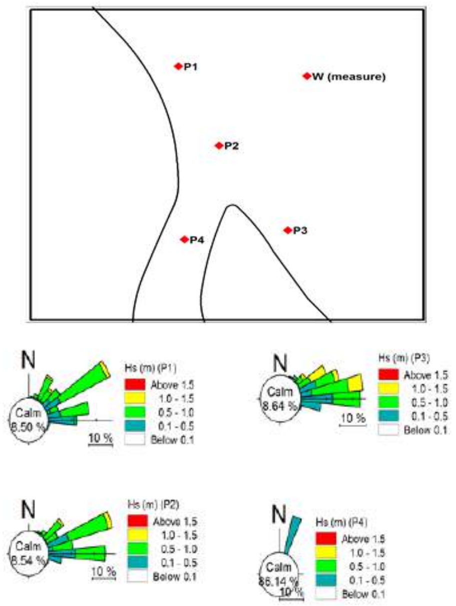

Fig. 7. Locations for wave extraction, (b) corresponding wave roses

2) Estuary Hydrodynamics

Figure 8 shows the peak velocities of ebb and flood tide velocities in three different situations: 1) tidal only forcing, 2) tides and Northeast waves in winter monsoon season, and 3) tides and Southeast waves in summer monsoon season. Snapshots of the depth-averaged currents during flood and ebb tide periods show the strong velocities in the tidal channel at the entrance due to the restriction of the entrance because of the elongating southern sandspit. The combination of tides and fresh water inflow causes much stronger ebb tidal velocity than flood tidal velocity (Figures 8(a) and 8(d)). The strongest flow velocities during flood and ebb tides at the entrance have an important role in maintaining the entrance and orienting the main channel. Away from the entrance, the flow currents decrease quickly over the ebb tidal delta. It can be seen that the tidal currents along the coast during the ebb tide are much stronger than during the flood tide, making the system to export sediments to the southern coast, i.e. the tidal currents transport fluvial sediment from the river mostly to the southern coast.

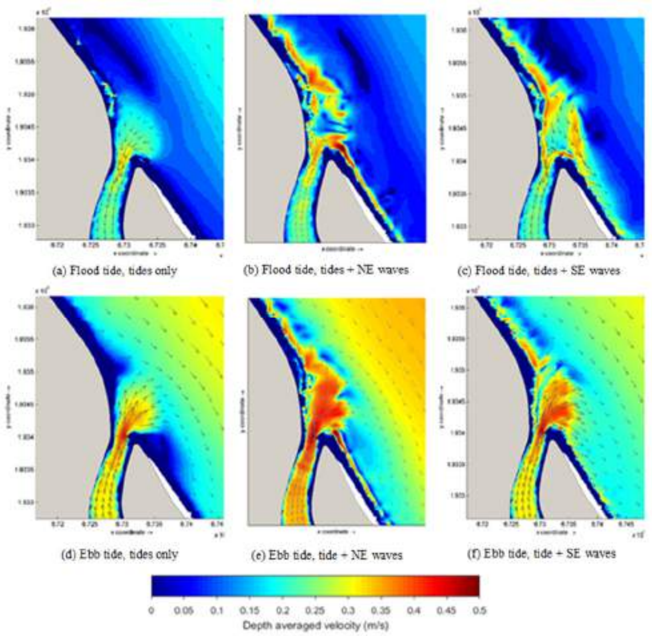

Fig. 8. Peak velocities during flood tide (top) and ebb tide (bottom) in different tide and seasonal wave conditions (axes units are meters)

In the case of wave present, the contribution of wave radiation stresses makes the flow field to be more complex. The results show that the long shore currents during the winter NE waves are much stronger than during the summer SE waves but both wave conditions generate long shore currents and long shore sediment transport in the SE-NW direction which cause the southern sandspit to elongate Northwest. Unlike the fresh water flow and tide only conditions, in the case of wave present both flood and ebb currents seem stronger and the flood currents are able to transport sediment from the ebb tidal delta and those delivered by long shore currents further landward thus reshaping the shores. The model results suggest that tidal and river flows dominate the main channel and the inner estuarine zone. Especially during high river discharge events, which are frequent over winter months, river discharge and ebb tides flush sediment seaward and then the offshore tidal currents will transport the sediment to supply the southern coast. Wave-induced circulations and alongshore currents prevail on the ebb tidal delta and in the near-shore region on both sides of the estuarine mouth. In the near-shore area away from the inlet, wave-induced circulation patterns are often driven by the interaction between the waves and the seabed. The strong wave radiation stress modifies the pattern of the depth-averaged velocity especially near to the coast and the sand bar due to wave breaking in this region. Under the condition of combined currents and waves, the flow magnitude increases considerably in the tidal channel and particularly in shallow water depths. It is specially noted that coastal waves induced by currents (e.g. tidal currents) could reach up to 0.5m/s in most of the coastline. These currents combined with tidal and river flow produce a jet that can reach the depth of 10m in ebb tide conditions.

3) Sediment Transport and Bottom Changes

Sediment transport and bottom morphological changes are simulated for various conditions of hydrodynamic and wave forcings. Sediment grain size is setup uniformly with d50=0.03mm based on bed core data. Tides, waves, and river discharge are the main parameters that effect on the sediment transport and morphology responses.

(a)

(b)

(c)

Fig. 9. Erosion/accretion processes are displayed by (a) simulation modeling, (b) Google Earth Image (Screenshot from Google Earth, Map data: Image@2015 Digital Globe, Image@2015 TerraMetrics and Maxar Technologies), and (c) survey data for the flood season in 2015

The simulations' performance was well-fitted to the measured data during the high flow season. It is observed that sediment has pushed away from the estuary to the ebb tidal delta (Figure 9). Alongshore wave-driven and tidal currents redistribute this sediment to accrete along the coastline. It is worth noting that during the low flow season, as a result of the long shore drift and sediment transport from the south which is weakly interrupted by the tides and river inflow, sediment continues to accumulate and deposit at the southern side of the ebb tidal delta and at the tip of the southern sandspit and causes the sandspit to develop northward (Figure 10).

(a)

(b)

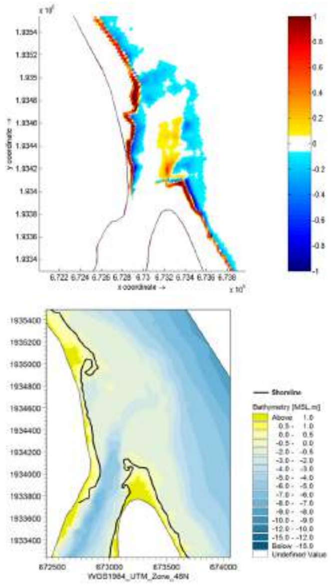

Fig. 10. Erosion/accretion processes are displayed by (a) simulation modeling and (b) survey data for a low flow season (2015)

V. CONCLUSIONS

This study presents the first attempt to fully couple hydrodynamic and morphodynamic models (MIKE and Delft3D) for a better insight into the morphology evolution of Nhat Le estuary, Vietnam. The simulations document a series of complexity trends under the ensemble effects of tides, waves, flows, and winds. The major physical processes governing the estuary morphology including tides, waves, and freshwater discharge were simulated. The model system was calibrated and validated using measured and observed data from 2005 to 2016. The simulations presented in this paper are, of course, limited to the particular sedimentary and morphological conditions of the Nhat Le estuary. Although the findings are not considered with sedimentary and geological evolution at the upstream of Nhat Le river basin and at a regional scale of north-central coast of Vietnam, they allow making hypotheses and conducting further research in a wider range. The results of the simulations are in accordance with the measured and observed data during the periods of calibration and validation. The results demonstrate that the seasonal variations of freshwater flow and ocean waves under the tropical monsoon regime significantly affect the behavior of the estuary morphology. The role of freshwater flow in the flood season is to cut off the southern sandspit, maintain, and shape the main channel. Sediment from the river is exported to the ebb tidal delta due to the ebb dominant freshwater inflow and tidal currents. Outside the estuary, ebb dominant tidal currents transport the sediment to the South and supply the southern coast. The prevailing waves in winter and summer induce long shore drift and sediment transport in the SE-NW direction. In the low flow season, this long shore sediment transport is dominant which causes sediment to deposite on the southern side of the ebb tidal delta and elongates the southern sandspit to narrow the estuary entrance and reorient the main channel.

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