Morphodynamics of tidal inlets in a tropical monsoon area

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Abstract
Morphodynamics of a tidal inlet system on a micro-tidal coast in a tropical monsoon influenced region is modelled and discussed. Influences of river flow and wave climate on the inlet morphology are investigated with the aid of process-based state-of-the-art numerical models. Seasonal and episodic behaviour of the inlet system under the influence of the forcing processes is then described, modelled and explained.

Introduction

The central coast of Vietnam is located in a tropical monsoon region and characterized as a microtidal, wave-dominated coastal environment. Tidal inlets in such condition are highly dynamic and variable under the influence of wave climate and river flow, which are seasonally varying according to the monsoon regime. Strong episodic influences of flow discharge and wave action have been mentioned as the cause of seasonal closure of tidal inlets as found on microtidal coasts of India (Bruun 1986), Sri Lanka (Wikramanayake and Pattiarachchi, 1999), Japan (Tanaka *et al.*, 1996), Australia (Gordon 1990; Ranasinghe and Pattiaratchi, 1997, 1998, 1999, 2003), South Africa (Cooper, 1990, 1994; Largier *et al.*, 1992), USA (Elwany *et al.*, 1998), and Brazil (Moller *et al.*, 1996). Many river mouths and tidal inlets along the central coast of Vietnam also have characteristics of seasonal closure. During the flood season, river floods have strong influence on their morphology by scouring channels and cutting through coastal barriers. In the dry season, wave action dominates over tide and river flow. Wave-induced sediment transport eventually closes some inlets or river mouths. To get further insight into the processes and behaviour of tidal inlets in the central coast of Vietnam, this paper will present a study on morphodynamics of Hue tidal inlets as a specific case study.

Study area

The Tam Giang-Cau Hai lagoon is located in Thua Thien-Hue province in central Vietnam. This is a system of connected lagoons and two tidal inlets connecting to the South China Sea. The lagoon has a surface area of 220 km² and elongates 70 km in NW-SE direction along the coastline. The lagoon water body is separated from the sea by a system of sandy barriers and island barriers. It receives water from the Huong River Basin which has a catchment area of about 4400 km² and discharges to the sea through two tidal inlets: Thuan An in the north and Tu Hien in the south (Figure 1). Under the tropical monsoon climatic conditions, the morphology of the inlets is highly dynamic and variable. The historical morphological changes of the inlets can be seen in Figures 2 and 3. The tropical monsoon regime exerts its influence on tidal inlet morphology through the variation of river flow and wave climate into two distinct seasons: the northeast and the southwest monsoon winds.

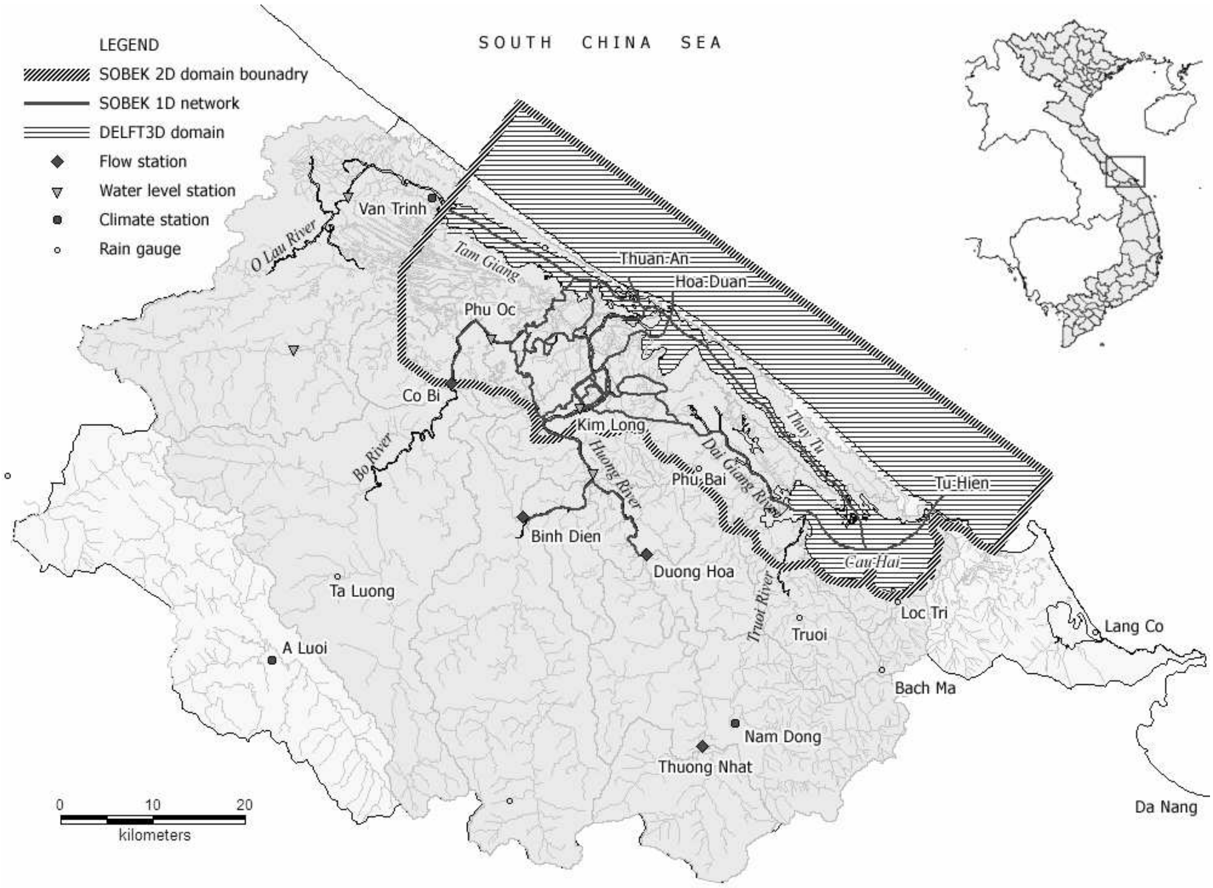


Figure 1 Numerical model domains of Hue coastal waters

Northeast monsoon season

The northeast monsoon prolongs from mid-October through February. After crossing the warm and humid South China Sea, it brings abundant precipitation to the coastal mountains of Central Vietnam. During the period from early September through November, typhoons also commonly strike along this coastline. The typhoons drive in from the east and rapidly dissipate into rain-storms when spoiled by the Truong Son Mountain Range on the west. Northeast winds and typhoons create a ‘wet’ or ‘flood’ season lasting from September through December. Although the flood season lasts only four months, it accounts for more than 70% the amount of the basin annual rainfall of 3100 mm. Torrential rainfall on the highly steep topography creates severe floods in the Huong river basin and heavy flooding in the coastal lowland area. During the flood season, the peak discharge of the Huong River may reach 12000 – 14000 m^3/s (Tuan et al. 2001). The floodwater not only flows in the river channels but it also overflows the floodplain with a few meters water depth.

Due to the flood the water level raises rapidly, so that the water level difference at two sides of the inlets may reach about 2 m, creating very high flow velocity in the inlets and causing dramatic changes to the inlet morphology. When flood water level exceeds the crest level of the sand barrier at the critical locations, barrier breaching also may happen at the weakest points to allow additional discharges. These consequences can be seen in a flood that occurred in early November 1999. A tropical depression with a maximum rainfall intensity of 120mm/hour occurred that has produced a serious flood of the central coastal provinces of Vietnam. The flood has enormously scoured tidal inlet channels. The cross-sectional area of the Thuan An inlet has increased from 3250 m^2 to 6200 m^2, and the cross-sectional area of the

Tu Hien inlet has scoured from to 600 m^2 to 1800 m^2. The flood also breached the sand barrier at Hoa Duan to create a new inlet with a cross sectional area of 1750 m^2 (Figure 2).

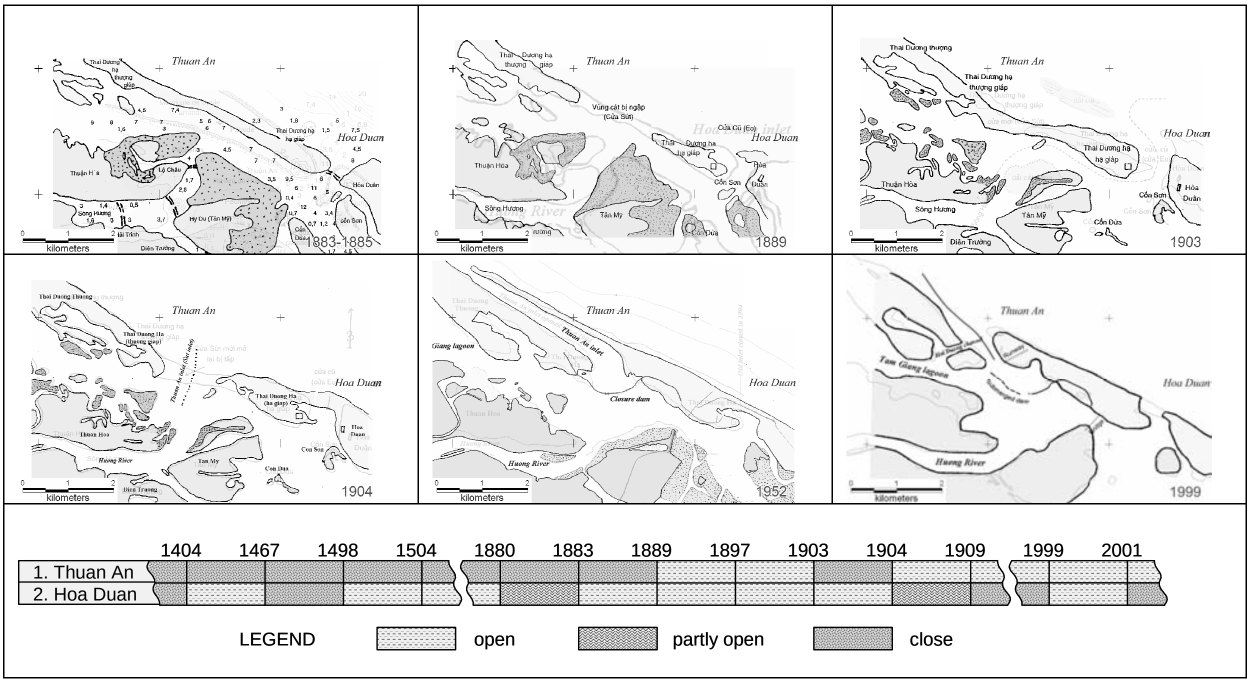


Figure 2 Historical development of Thuan An inlet

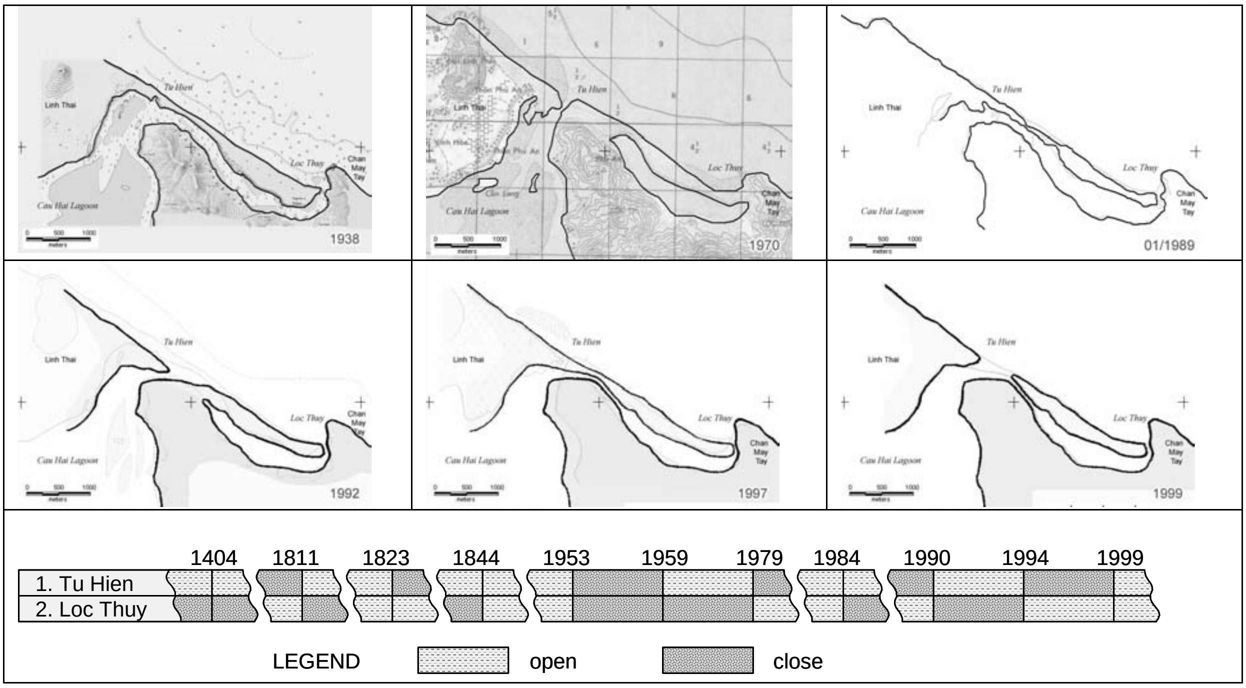


Figure 3 Cyclic evolution of Tu Hien inlet

Flood flow transports sediment from the river basin to the lagoon and inlet areas. An estimation made by Lee (1970) is about 350,000 m³/year sediment contribution by the rivers to the lagoon but most of it is deposited inside the lagoon areas, with only 15% of that amount is transported to the sea through the tidal inlets. Coarse materials may be deposited in the ebb tidal deltas but fine wash-load would be dispersed by wave action and removed from the littoral shoaling zone.

Figure 4 shows the wave climate observed at Con Co Island situated 72 km offshore NNW of the Thuan An inlet. During the northeast monsoon season, northeast winds create a rough sea with dominant waves come from N, NE or NW. Northeast monsoon waves usually cause coastal erosion.

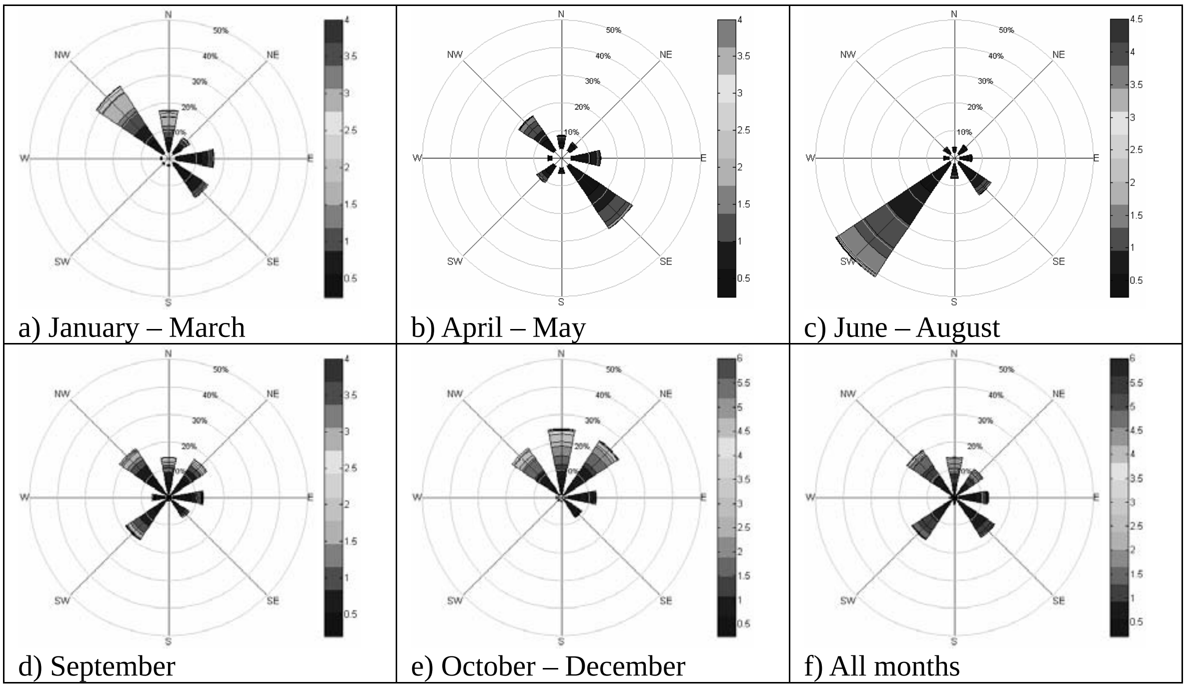


Figure 4 Wave roses at Con Co Island based on 1992-2001 observations

Southwest monsoon season

During the remaining eight months of the year, river flow significantly diminishes making this period a ‘dry’ season. Especially, when the southwest monsoon takes over from May until September, when the southwest winds after passing the Truong Son Mountain Range have been dried out and become very hot, river flows become lowest. In this season, waves come from SE inducing longshore sediment transport northwestward on the coasts near the Thuan An inlet. Because the tidal range in the area is only 0.41 m (that is smallest along the Vietnamese coast), wave action becomes dominant in the inlet areas.

Characterized as micro-tidal wave dominated, the tidal inlets become unstable with shoals developing and sand spits migrating. Longshore sediment enters the Thuan An inlet and shoals its channel and ebb tidal delta hampering navigation. Prevailing longshore sediment transport from SE causes the inlet to gradually migrate northwestward (Figure 2). In the Tu Hien inlet, because a rocky headland limits the coast just at the southern side of the inlet so the dominant sediment transport entering the inlet is mainly from the northwest direction. The northern sand spit gradually develops and grows southeastward (Figure 3). During the next flood seasons, if river flows cannot breach through the sand spit, the spit will continue to develop and pushes the channel to migrate southeastward. At the end of the inlet migration and development process, the entrance is relocated at Loc Thuy nearly 3 km south of the original location Tu Hien, the channel width decreases from 200 m to about 50 m and the depth decreases from 3 - 4 m to less than 1 m. This cyclic development usually takes many years. The last cycle took 9 years starting in 1990 at Tu Hien and relocated at Loc Thuy in the period 1994-1999 until the historical flood of November 1999 happened (Figure 3). According to Thanh et al. (2000), the morphologic cycle now becomes shorter.

Numerical models

Hydrodynamic model for river flows

A numerical model of river flow hydrodynamics has been setup based on SOBEK-RURAL with the integration of a 1D module for river channel flow and a 2D module for overland flow on the floodplain (Figure 1). The 2D part of the model covers all the areas of the lagoon and the coastal lowland with a DEM of 200 m resolution. The 1D river channel network does not only superpose the DEM but also extends 45 – 65 km upstream to include the flow and water level stations so that the observations at these stations can be used for the upstream boundary conditions as well as for model calibration and verification. Downstream boundary conditions of the model are tidal water levels off the inlets. Upstream boundary conditions of the models are flow discharges at the observation stations. The model has been calibrated and validated for some flood events including the floods of November 1999 and October 1983.

Morphodynamic model for lagoon and inlet system

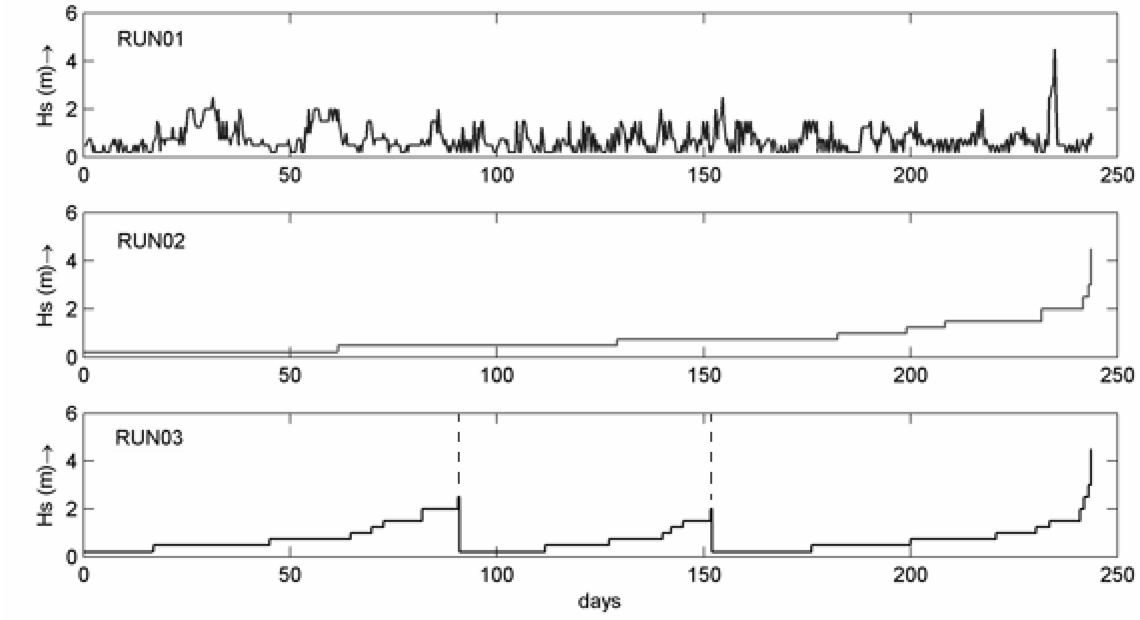


Figure 5 Input wave data for computational schematizations RUN01, RUN02 and RUN03

The results from the hydrodynamic model for river flow are used as boundary conditions for the detailed morphodynamic model of the lagoon and inlet system. This model has been setup in Delft3D including in its domain the lagoon and inlets and extended to the continental shelf at a water depth of 30 m. The model grid is curvilinear with a minimum grid size at the inlet locations of less than 50 m. In addition to the river flows and tidal forcing, the actions of waves and winds are also taken into account in the model. Information about waves and winds is derived from the observed data at Con Co Island (Figures 1,4). Besides the Delft3D-WAVE and Delft3D-MOR modules in the Delft3D modeling packages, the 2D version of Delft3D-FLOW has been applied for this case. For the long-term morphologic simulation of the system, the "morphological factor" technique (Roelvink, 2006) has been applied. As shown in Figure 5, different schematizations of input wave data series have been applied. RUN01 is the “traditional” time sequence of the actual observed wave height and wave direction. RUN02 is the input data of the same wave height series which has been grouped into classes of wave height in the ascending order. Each class has a morphological factor corresponding to the time portion of its occurrence in the whole computational period and the wave direction is sorted increasingly. RUN03 uses the same approach as RUN02 but the schematization is “staged” and applied for each period of different monsoon winds or climatic conditions.

Results and discussions

River flow influences

During river floods, very strong flow can occur in the inlets. For example, maximum velocity in the Thuan An and Tu Hien inlets during the flood of November 1999 can reach 3.7 m/s and 2.0 m/s, respectively. At the inlet, water flows as a strong flow jet which widens and deepens the inlet channel and gorge. Strong currents due to river-flood scour the Thuan An inlet channel and deepen its bottom level from -10 m to -14 m. Figure 6 shows the simulated bottom erosion and accretion pattern of the Thuan An inlet in the flood November 1999 that is very similar to the topographic survey data.

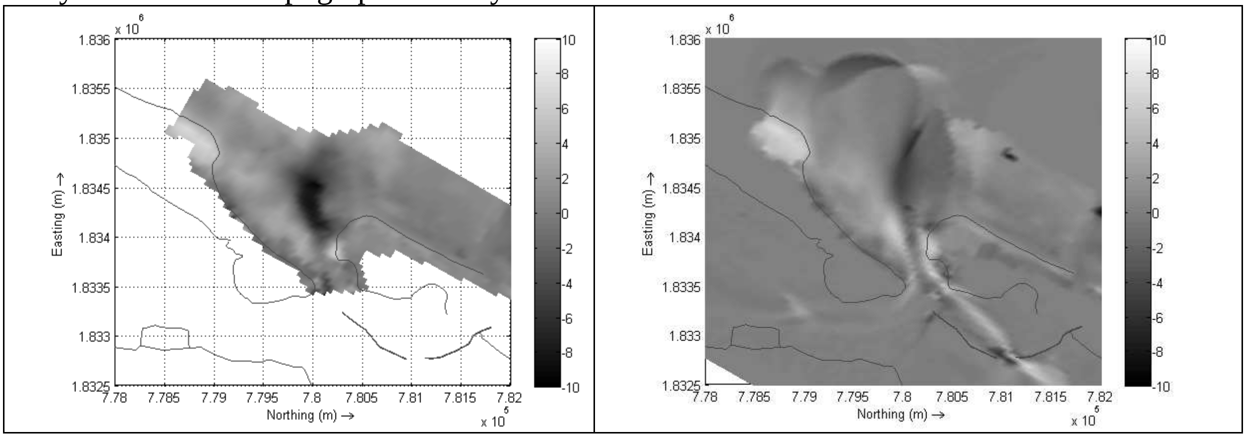


Figure 6 Bottom changes at Thuan An inlet from 1999 and 2002 surveys (left) and simulation (right)

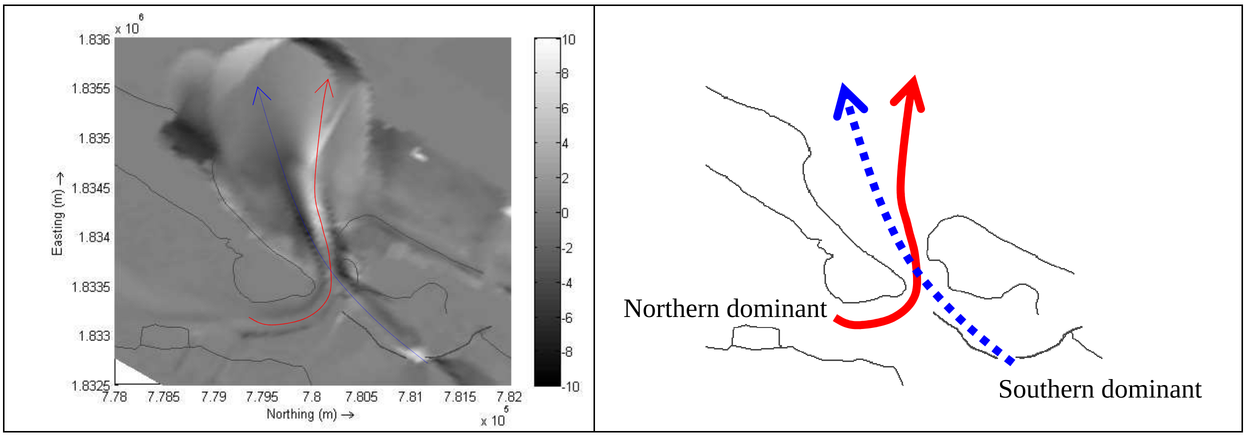


Figure 7 Influence of river floods on Thuan An channel orientation

In the Thuan An inlet channel and its ebb tidal delta, the direction of the flow jet is relatively stable. Figure 7 shows that the direction of the flow jet in the inlet and the ebb delta depends on the side which the dominant river flood discharge comes from. If the flood water dominantly comes from the southern side of the inlet, i.e. mainly contributed by the rainfall on the Huong River catchment, the jet current will head north or northwest and turn the inlet channel to the same as its direction. If the flood water coming from the northern side is stronger caused by much rainfall happening on the northern catchments of the O Lau and Bo rivers then the jet current will have a tendency to become perpendicular to the coast that turns the inlet channel to the northeast direction. Depending on the direction of the flow jet, the inlet channel is reoriented accordingly.

Outside the ebb delta, the flow direction changes according to the tidal currents in the sea in the along shore direction. Sediment is mainly removed in the channel and the ebb delta and transported to the terminal lobe of the ebb tidal delta where the flow velocity decreases significantly.

During the non-river flood periods, because the inlet cross-sections were scoured largely, the flow currents in the inlets drop significantly. For instance, the magnitude of flow current in the Thuan An inlet reduces to less than 0.5 m/s just after the flood of November 1999. With this velocity, the inlet is unable to transport out the sediment deposited in the inlets. There is almost no sediment transported from the inlet into the lagoon and the flood tidal delta cannot be formed.

Medium-term inlet deposition in dry season

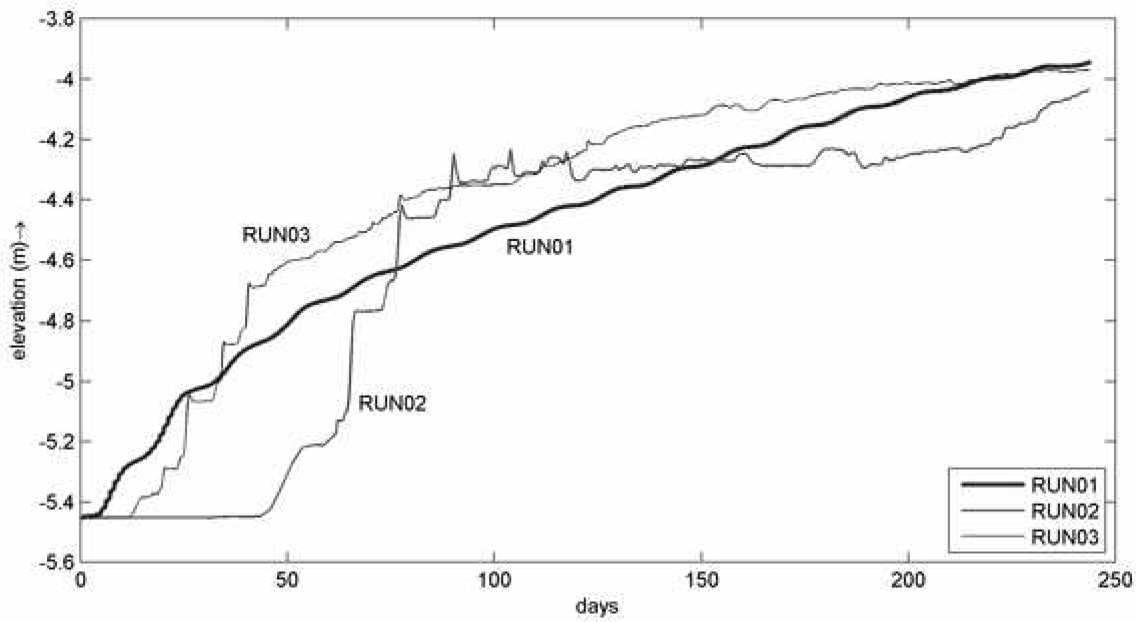


Figure 8 Bottom evolution of the Tu Hien Inlet

Figure 8 plots the deposition process in the Tu Hien inlet according to different wave data schematizations. At the check point in the inlet, inlet bottom is deposited about 1.5 m from -5.5m to -4.0m during 8 months of the dry season. The actual time sequence of wave observed data (RUN01) shows a gradually bottom deposition in the inlet. But this approach requires wave computation carrying out for every observed data that needs a lot of computational effort and time consuming. The schematized wave data of RUN02 and RUN03 produce sudden changes in the deposition process. The changes and the shape of the evolution curves depend on the occurrence of each wave height and wave direction of the schematizations. The sudden changes of bed deposition mostly happen during the northeast monsoon period when longshore sediment transport to the inlet from northwest is strongest. Nevertheless, the final bottom elevations of the inlet at the check point according to different wave schematizations are close to each other. The “staged” schematization of RUN03 has the bottom evolution curve most closely to those of the actual time sequent input RUN01 but it requires more computational effort than RUN02. Therefore the “morphological factor” approach can be used for longer simulations with less computational efforts.

Wind wave influences

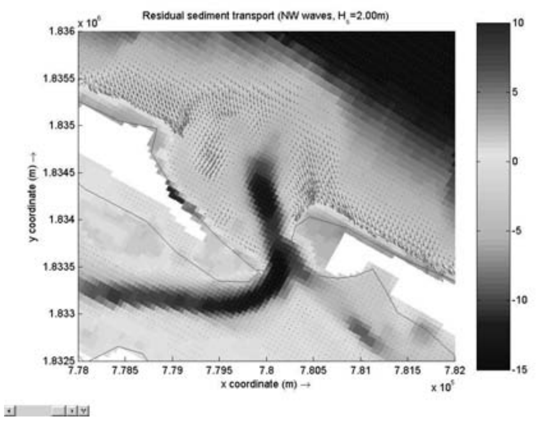
In the dry season which lasts eight months from January to August, the morphology of the inlets is mainly influenced by the action of waves and tides. The morphological change in the inlet areas then behaves correspondently to the seasonal variation of wave action.

The wave climate observed at Con Co shows that, during the month of September when the southwest monsoon ends and the northeast monsoon starts, the dominant waves may come from NW, NE or SW depending on the domination of which monsoon wind in that period (Figure 4d). In the next months from October to December, the northeast monsoon winds become most active and the dominant waves are mainly from N or NE directions (Figure 4e). The months from September through December are also the period in which typhoons and tropical cyclones operate most actively. Therefore in these months, the sea is quite rough with wave heights of about 1.5 – 2.5 m. Waves during the typhoons may be as high as 6 m. But these months are also the flood season when the inlets are dominated by the river flows so the influences of sea waves are mainly restricted to the coasts.

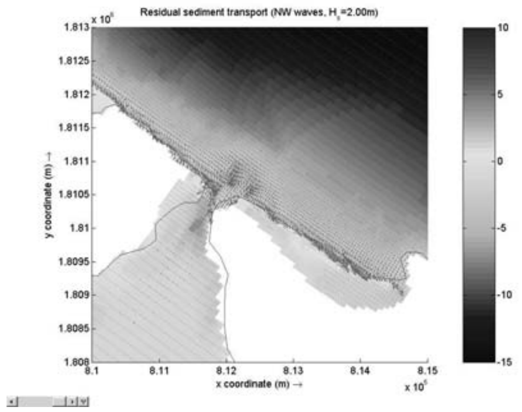
In the end of winter from January through March, the prevailing waves are NW with the significant wave height H_S = 1 – 2 m (Figure 4a). Because the alignment of the coastline is in the NW – SE direction, the magnitude of the southeastward longshore sediment transport is largest in these months (Figure 9a,b). In this period, just after the inlet channels have been deepened by the river floods and when the river flow diminishes, the channel cross sections become too large and the tides are too weak to remove the sediment entering the inlet channels. The inlets are hungry for the sediment and become the large sediment sinks. They cause the erosion of the adjacent coasts at both sides of the inlets, especially the updrift coasts on the northern sand barriers of the inlets. The evidence for this can be seen at the coast of Hai Duong commune located on the north side of the Thuan An inlet. Every year, along 3 km of this coast near the Thuan An inlet, the sand dune is eroded for 15 – 20 m during the winter time. The beach is accreted back 10 – 15 m during the summer months resulting in a retreat rate of this beach of approximately 5 m/year (Hoi et al., 2001). Simulation results also show that the southeast monsoon waves in these months gradually move onshore part of the sediment which is transported to the terminal lobe by the river floods to fill in the channel and build up the ebb deltas and the coasts.

In beginning months of summer from April to May, the sea is rather calm with small dominant SE wave of less than 1 m high (Figure 4b). The combination of the shoreline direction and the wave direction creates the strongest longshore sediment transport in the northwestward direction by the summer monsoon. Because the southern coast of the Tu Hien inlet is blocked by a rocky headland at Loc Thuy so the longshore sediment transported to the inlet is limited (Figure 9c,d). On this coast, the sediment transported by waves is mainly to build up the small sand barrier. During the most active months of the southwest monsoon winds from June to August, the offshore waves at Con Co come dominantly from SW direction (Figure 4c). In the nearshore areas the waves which are mainly swell waves, are quite calm and rework the beaches and the ebb deltas.

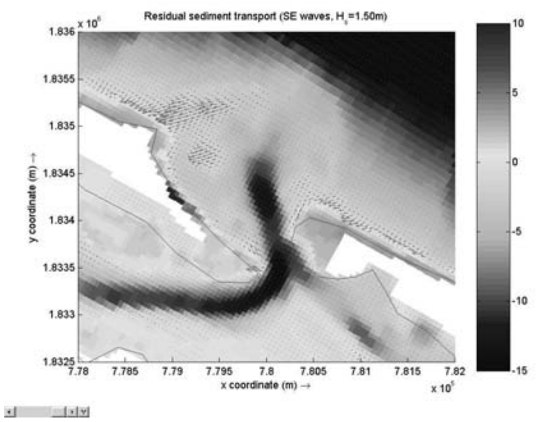
Small waves and swell in the summer months rework the sediment and transport it onshore. The beaches are restored by onshore sediment transport. The ebb tidal deltas are moved back and become smaller in size. The tidal channels are filled up and the bars in the deltas develop. These developments continue until the system getting the equilibrium state. If the equilibrium is reached then sand by passing in the ebb deltas and the migration of updrift sand spits and sand bars in the ebb deltas will happen. After some severe river floods it may take the Thuan A period of nearly 10 years is needed to regain the equilibrium state (Lam, 2005). When it reaches the equilibrium state, the maximum growing speed of the southern sand spit at the Thuan An inlet can be at the order of about 15m/year according to observations (Hoi et e., 2001).



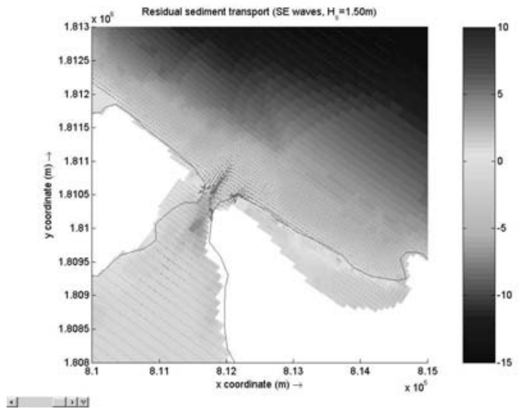
a) Thuan An inlet, NW waves



b) Tu Hien inlet, NW waves



c) Thuan An inlet, SE waves



d) Tu Hien inlet, SE waves

Figure 9 Residual sediment transport in the inlets

Conclusions

Medium-term morphodynamics of tidal inlets in Hue has been simulated and described with the help of numerical models. The episodic influences of river flow and wave climate follow the tropical monsoon regime and make the tidal inlet morphology also seasonally varying and highly dynamic. The inlets are river dominated during the wet season. River flood is the main process to keep the inlets open and reorient the inlet channel. Sediment is exported from the river basins through the inlets. During the dry periods, the tidal inlets are wave-dominated and act as sediment sinks. The variation of wave climate determines the change of coastal deposition/erosion pattern. For a longer simulation period with less computational effort, the approach of 'morphological factor' is applicable.

Acknowledgments

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