

# Hydrodynamics and morphodynamics of a seasonally forced tidal inlet system

Nghiem Tien Lam<sup>1</sup>, Marcel J.F. Stive<sup>2</sup>, Zheng Bing Wang<sup>3</sup>,  
Henk Jan Verhagen<sup>4</sup>, Vu Thi Thu Thuy<sup>5</sup>

**Abstract:** Hydrodynamics and morphodynamics of a seasonally forced tidal inlet system are investigated using numerical models. The ocean forcing including tidal and wave actions and sediment transport is simulated using Delft3D model. Fluvial processes in Delft3D are taken into account as results from SOBEK-RURAL model. Analysis of the numerical simulation results allows enhancing insight the mechanisms behind the behaviours of the tidal inlet system in a tropical monsoon area under the influences of river flow and seasonal wave actions.

**Keywords:** tidal inlet, hydrodynamics, morphodynamics, monsoon.

## 1. Introduction

The Tam Giang-Cau Hai lagoon is located in the Thua Thien-Hue province in central Vietnam. This is a system of connected lagoons and two tidal inlets linking with the South China Sea. The lagoon has a surface area of 216 km<sup>2</sup> and elongates 68 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 km<sup>2</sup> and discharges to the sea through two tidal inlets: Thuan An in the north and Tu Hien in the south (Figure 1).

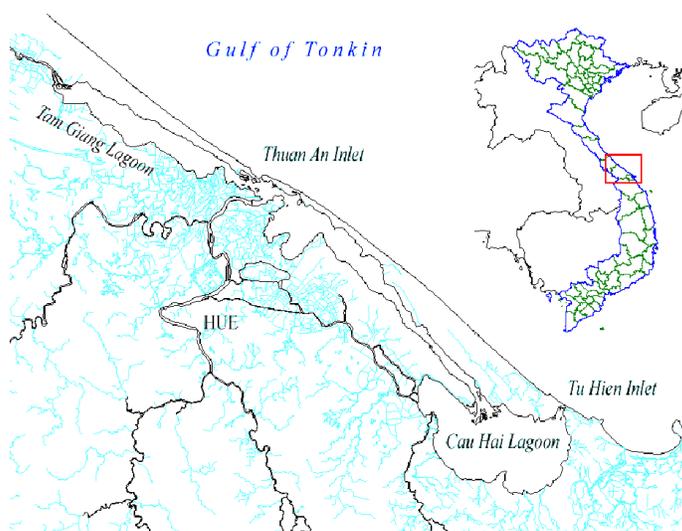


Figure 1: Tam Giang-Cau Hai lagoon and tidal inlet system

The area is located in a tropical monsoon region and is characterized as a microtidal, wave-dominated coastal environment. Under the tropical monsoon climatic conditions, the morphology of the inlets is highly dynamic and variable. The tropical monsoon regime exerts its influence on the tidal inlet morphology through the seasonal variation of river flow and wave climate. However, the forcing

<sup>1</sup> Faculty of Marine and Coastal Engineering, Water Resources University; 175 Tay Son, Hanoi, Vietnam; E-mail: lam.n.t@wru.edu.vn

<sup>2</sup> Prof., Dr., Ir.; Delft University of Technology, Faculty of Civil Engineering and Geosciences; P.O. Box 5048, 2600 GA Delft, The Netherlands; E-mail: M.J.F.Stive@tudelft.nl

<sup>3</sup> Dr., Ir.; WL | Delft Hydraulics and Delft University of Technology; P.O. Box 177, 2600 MH Delft, The Netherlands; E-mail: zheng.wang@wldelft.nl

<sup>4</sup> Ir.; Delft University of Technology, Faculty of Civil Engineering and Geosciences; E-mail: H.J.Verhagen@tudelft.nl

<sup>5</sup> Water Resources University; 175 Tay Son, Hanoi, Vietnam; E-mail: thuy.kcct@wru.edu.vn

mechanisms of waves and river flows which determine the morphologies of the tidal inlets are still poorly understood. This paper presents an analysis on the mechanisms of waves and river flows associated with sediment transport and morphological change at the Thuan An and Tu Hien inlets based on a numerical modeling approach.

## 2. Numerical models and boundary conditions

Two process-based simulation models of Delft3D and SOBEK-Rural developed by WL | Delft Hydraulics are used for the study. SOBEK-Rural (WL | Delft Hydraulics, 2001) is selected to simulate river flows to the inlet areas because its integration of the 1D Channel Flow for flows in the rivers and the 2D Overland Flow for overflows on the floodplain is most suitable for the flooding situations in the coastal lowland area of Thua Thien-Hue. The model domain of river flow in SOBEK-Rural is shown in Figure 2. The network of the 1D Channel Flow is from gauging stations to the inlets whilst the domain of the 2D Overland Flow covers only the lowland area. Upstream boundary conditions of the model are flow discharges measured or computed using hydrologic models at the stations of Duong Hoa (Ta Trach river), Binh Dien (Huu Trach river), Co Bi (Bo river) and on the rivers of O Lau and Truoi. Model downstream boundary conditions are tidal levels in the sea off the inlets.

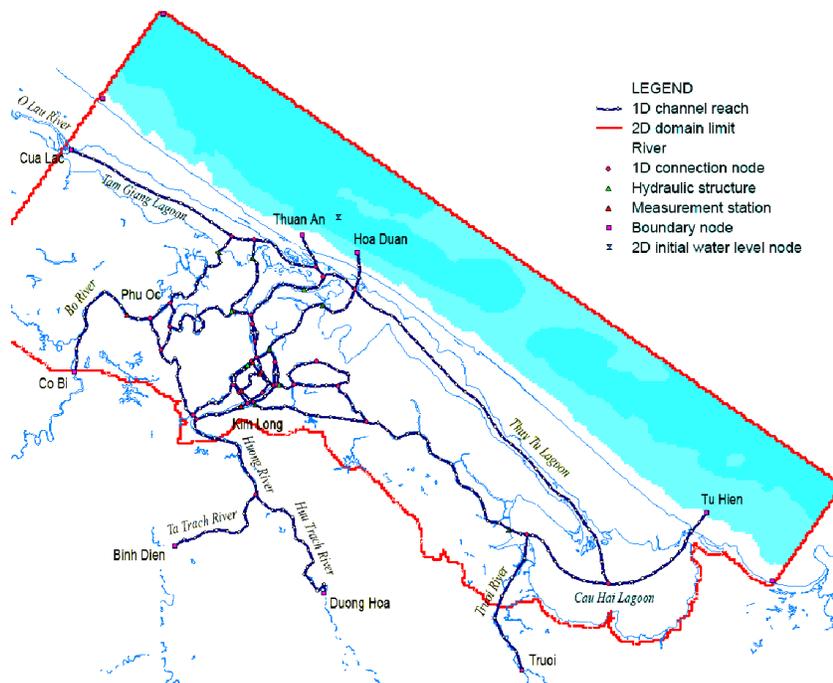


Figure 2: Model of rivers, floodplains, lagoons and tidal inlets using SOBEK-Rural

Delft3D is used to simulate hydrodynamics and morphodynamics in the inlet areas. It is integrated from Delft3D-WAVE and Delft3D-FLOW modules. SWAN wave model is used in Delft3D-WAVE (WL | Delft Hydraulics, 2006b) for wave propagation and transformation in nearshore. Delft3D-FLOW (WL | Delft Hydraulics, 2006a) is a module for simulating hydrodynamics, sediment transport and bottom changes. The model domain of the lagoon system and a part of the continental shelf is shown in Figure 3. Landward boundary conditions of Delft3D-FLOW are hydrodynamic results from SOBEK-Rural. Its seaward open boundary conditions are tidal water levels in the sea.

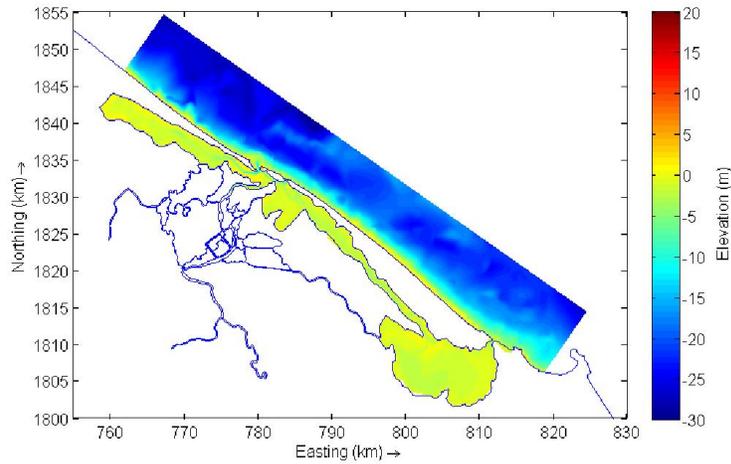


Figure 3: Model domain and bathymetry of the lagoon and inlet system

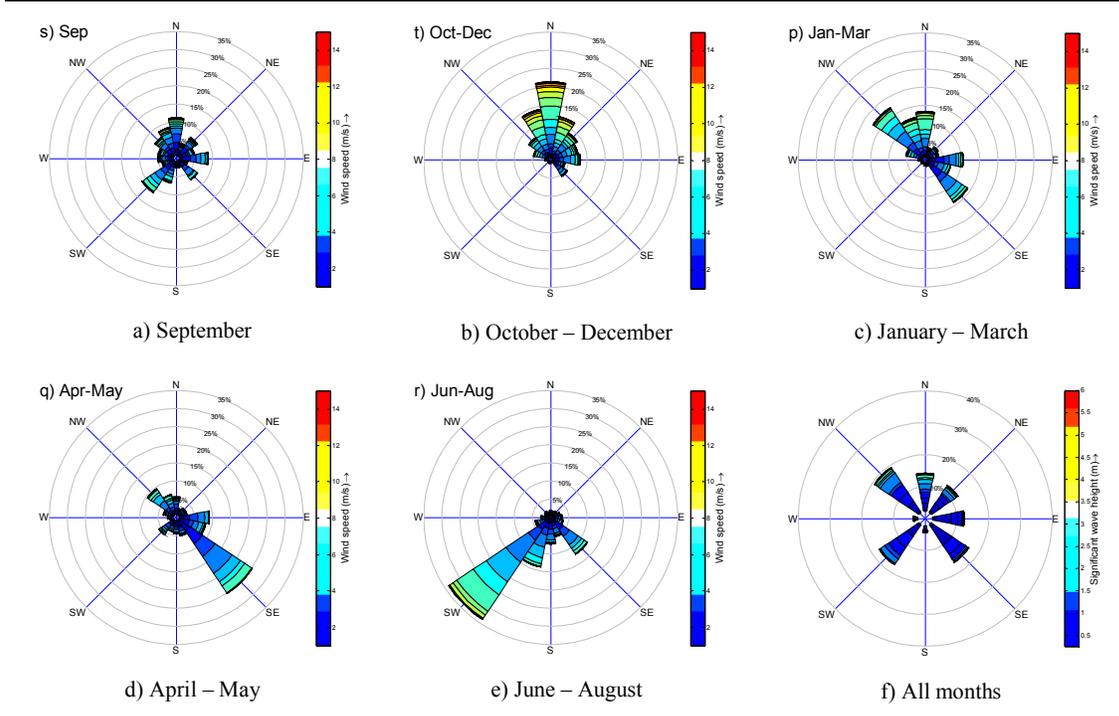


Figure 4: Wave climate at Co Co based on 1992-2001 observations

Boundary conditions of Delft3D-WAVE are wave data observed at Con Co from 1992 – 2001. The seasonal variation of wave directions at Con Co is shown in Figure 4. Depending on the dominant wave direction which is resulted from monsoon regime, the wave climate can be divided into 5 periods as in Figures 4a – 4e. September is the period of strong typhoon influence in the area and is the time when the northeast monsoon begins. Intermittent cold surges of NE monsoon winds interact with other weather phenomena to produce a scatter in wave direction (Figure 4a) and to start the flood season with torrential rains. The second period is from October-December when the northeast monsoon

flourishes creating dominant N waves (Figure 4b). January-March is the end period of the northeast monsoon with prevailing waves from NW (Figure 4c). The transitional period between the northeast and southwest monsoon is April-May with predominant waves from SE (Figure 4d). June-August are the months of southwest monsoon dominance when offshore waves come from SW (Figure 4e).

Sediment transport is computed with Van Rijn (1984a; 1984b) formula for bed load and suspended load carried by river flows and Bijker (1971) formula for waves and currents. Two grades of the sediment particles  $D_{50} = 200 \mu\text{m}$  and  $D_{50} = 390 \mu\text{m}$  are used.

### **3. Results and discussions**

#### ***3.1. Seasonal sediment transport patterns by waves***

The sediment transport patterns of typical wave directions at the Thuan An and Tu Hien inlets are shown in Figure 5. During the winter monsoon when dominant wave directions are N or NW, the rough sea condition creates strong longshore currents to SE that produces net longshore sediment transport to SE (Figure 5a, b). The general pattern of sediment movement is onshore in the outside areas of the inlets. At the Thuan An inlet, the winter waves move sediment from marginal shoals to sand spits. The waves also transport landward the sediment at the outside area of the ebb tidal delta to build up the offshore bars and narrow the ebb delta. The same processes also happen at the Tu Hien inlet caused by N and NW waves but at a smaller scope in space and at a shorter scale in time. The wave induced-sediment transport quickly fills up the channel and builds up offshore bars in the ebb tidal delta. Due to a shallow inlet channel, longshore sediments easily enter the Tu Hien inlet by following marginal flood currents. In consequence of the offshore bar building is the sediment by-passing on its ebb tidal delta to SE direction.

With other wave directions from NE, E or SE, the general direction of net longshore currents and sediment transport are opposite to NW (Figure 5c, d). The waves move onshore the sediment and offshore bars. Bar by-passing of the sediment on the ebb deltas also occur but to NW direction. At the south coast of the Thuan An inlet, the longshore sediment is transported to the inlet channel while at its north coast, sediment is moved from marginal shoals to the sand spit. The Tu Hien inlet is sheltered from SE waves by the Cape of Chan May Tay. Due to a lack of sediment supply from its southern coast, sediment entering the Tu Hien inlet mainly follows the northern marginal flood currents and part of it is flushed out by the ebb currents.

The seasonal monsoon regime has a strong influence on the wave climate and sediment transport pattern in the inlet areas. The seasonal variation of sediment transport induced by waves is extracted from model results for transects at the inlets as in Table 1. The transect names and positive directions of sediment transports in Table 1 are defined as in Figure 6.

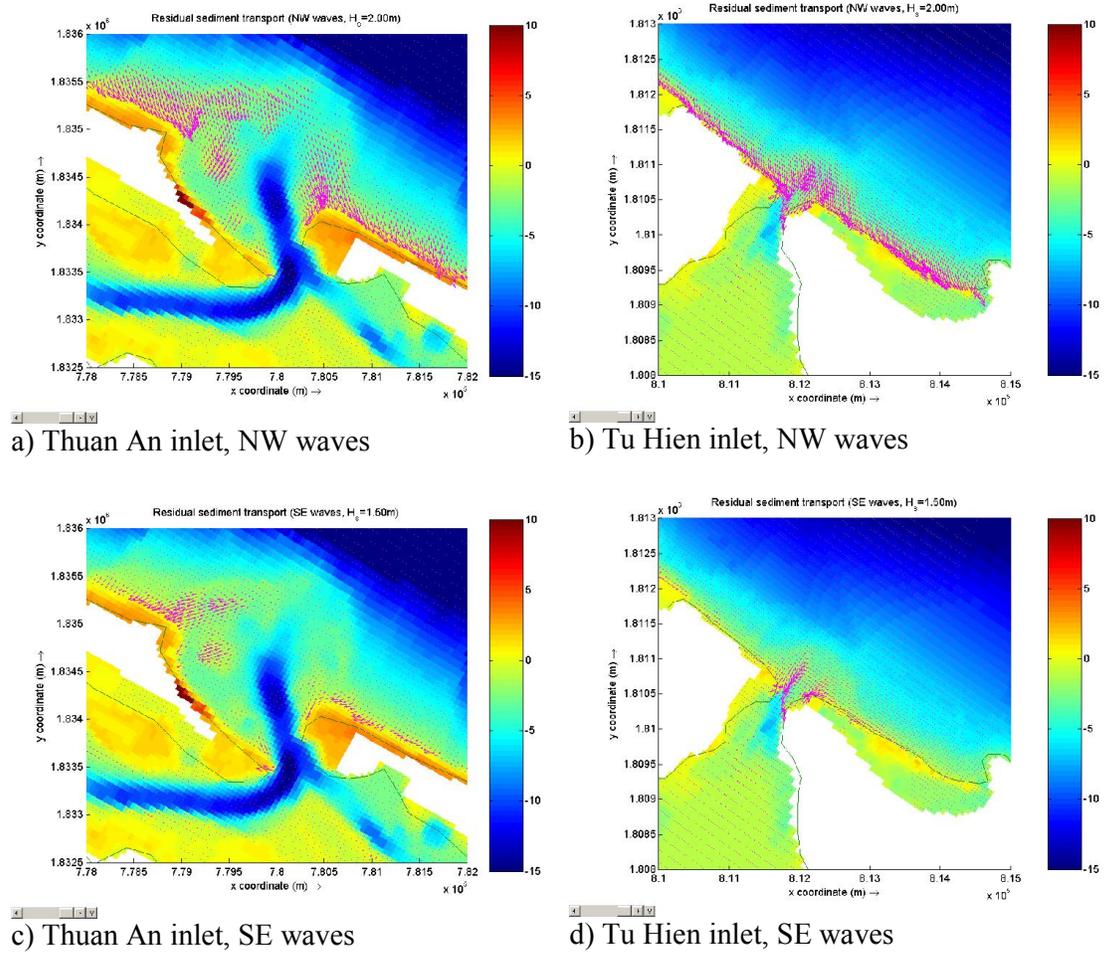


Figure 5: Residual sediment transport in the inlets

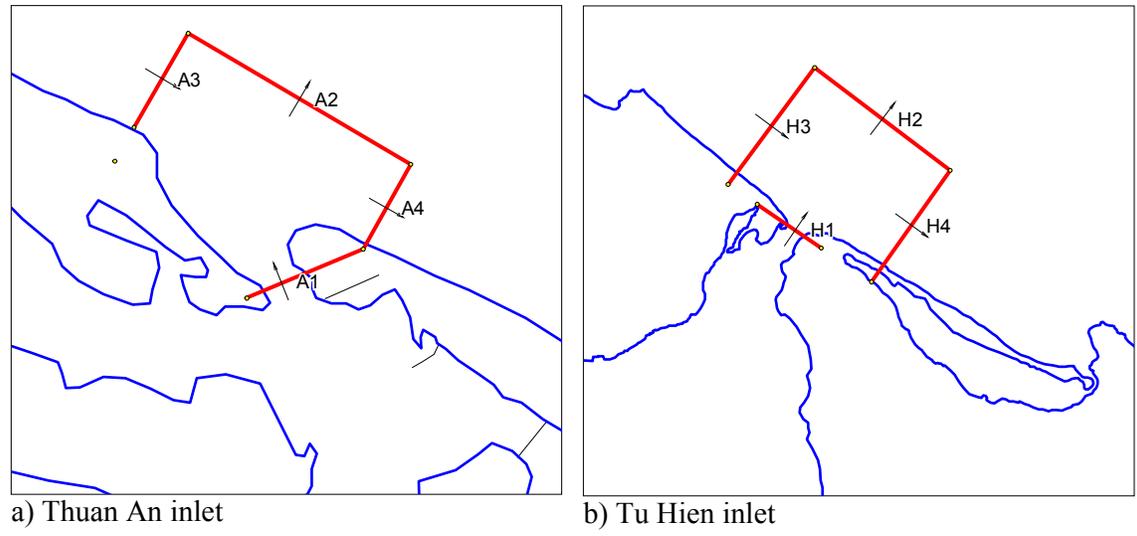


Figure 6: Transects and arrows show positive directions for sediment transport computation at inlets

Table 1: Sediment transports through transects (Mm<sup>3</sup>/year)

Period	Transport	Thuan An				Tu Hien			
		A1	A2	A3	A4	H1	H2	H3	H4
Jan-Mar	(+)	0.098	0.032	0.186	0.193	0.014	0.008	0.208	0.204
	(-)	-0.017	-0.035	-0.147	-0.137	-0.019	-0.004	-0.057	-0.115
	Net	0.081	-0.003	0.038	0.057	-0.005	0.004	0.151	0.089
Apr-May	(+)	0.065	0.027	0.032	0.033	0.013	0.006	0.036	0.035
	(-)	-0.003	-0.075	-0.046	-0.047	-0.017	-0.002	-0.043	-0.047
	Net	0.062	-0.048	-0.014	-0.014	-0.004	0.004	-0.008	-0.012
Jun-Aug	(+)	0.184	0.036	0.005	0.006	0.017	0.008	0.006	0.006
	(-)	-0.004	-0.017	-0.034	-0.034	-0.015	-0.002	-0.031	-0.034
	Net	0.180	0.019	-0.028	-0.028	0.002	0.006	-0.025	-0.028
Sep	(+)	0.523	0.767	0.022	0.024	0.042	0.033	0.027	0.025
	(-)	-0.003	-0.046	-0.043	-0.040	-0.013	-0.001	-0.014	-0.032
	Net	0.520	0.721	-0.021	-0.016	0.029	0.032	0.013	-0.007
Oct-Dec	(+)	0.562	0.635	0.384	0.403	0.078	0.064	0.447	0.429
	(-)	-0.048	-0.075	-0.719	-0.651	-0.036	-0.006	-0.179	-0.517
	Net	0.514	0.560	-0.335	-0.248	0.042	0.058	0.268	-0.088
Yearly	(+)	1.432	1.497	0.629	0.659	0.164	0.119	0.724	0.699
	(-)	-0.075	-0.248	-0.990	-0.909	-0.100	-0.015	-0.324	-0.745
	Net	1.357	1.249	-0.360	-0.249	0.064	0.104	0.400	-0.047

### 1) Sediment transport at Thuan An Inlet

It can be seen from Table 1 for transects A3 and A4 that the net longshore sediment transport in the Thuan An inlet area is about 0.25 – 0.36 Mm<sup>3</sup>/year to NW direction. This amount occurs almost in the months from October to December with a magnitude of 0.25 – 0.35 Mm<sup>3</sup>. In other months the net longshore sediment transport to NW direction is around 0.01 – 0.03 Mm<sup>3</sup> except the period of January – March with the longshore sediment transport is 0.04 – 0.06 Mm<sup>3</sup> but in SE direction. The net longshore sediment transport to NW direction indicates the growing direction of the southern sand spit to NW. The growth of the southern sand spit at the Thuan An inlet to NW with the maximum speed of 15m/year was reported in Hoi *et al.* (2001).

The sediment transported into the inner Thuan An channel happens mostly in the periods from October to March when river flow has weakened. In the period from October to December, 0.048 Mm<sup>3</sup> of sediment is transported back while this value in the period from January to March is 0.017 Mm<sup>3</sup>.

The total sediment transport from the rivers through the Thuan An inlet is 1.43 Mm<sup>3</sup> per year during the flood season. All of this sediment amount together with 0.065 Mm<sup>3</sup> of sand in the ebb tidal delta are moved offshore by river floods. During the low river flow periods, about 0.25 Mm<sup>3</sup> sand is transported back to the ebb delta but only 0.075 Mm<sup>3</sup> sand is transported into the inner inlet channel. Over a year, the sediment transports through the transects at the Thuan An inlet are almost balanced. Among 1.36 Mm<sup>3</sup> of net sediment is transported from the river system, about 0.11 Mm<sup>3</sup> is transported following the longshore current to north and 1.25 Mm<sup>3</sup> is transported offshore and follows tidal current to south building up offshore bars which are visible in bathymetric maps.

## 2) Sediment transport at Tu Hien Inlet

The annual gross longshore sediment transport at the Tu Hien inlet is about  $0.7 \text{ Mm}^3/\text{year}$ . The variation of longshore sediment transport at the Tu Hien inlet follows almost the tendency at the Thuan An inlet, except the amount of sediment transport to NW direction of the transect H3 on the northern side of the inlet is much lower in the months from September to March. This results to the net longshore sediment transport from the northern coast to the inlet area of  $0.4 \text{ Mm}^3$  while the contribution from the southern coast is only  $0.05 \text{ Mm}^3$ . The difference in longshore sediment transport can be due to the southern coast is sheltered from a portion of wave action by the headlands at Loc Thuy and Cape of Chan May Tay which is also a reason for a limited sediment budget stored on this coast. The gross longshore sediments which enters both inlets are at the same order of about  $0.7 \text{ Mm}^3/\text{year}$  and their tidal ranges are almost the same, but the big differences in the magnitude of annual river flow and peak flood discharge make the two inlets having different stability conditions.

The total sediment transported from the rivers and lagoon through the Tu Hien inlet is only  $0.164 \text{ Mm}^3$  per year but  $0.100 \text{ Mm}^3$  of sand is transported back to the inlet channel and its flood tidal delta during the low flow periods.

### **3.1. River influences**

#### *a) Hydrodynamics of a river flood in November 1999*

Based on the model simulations for river floods, the hydrodynamics in the situation of the historical flood in November 1999 is discussed. Figures 7 and 8 show computed water levels in the lagoon and flow velocities in Thuan An and Tu Hien inlets. The peak water levels in the lagoons can be seen very high near the inlets. These values at Thuan An and Tu Hien are 2.64 m and 2.80 m above the datum (MSL), respectively. This is due to too much flood water flows to the lagoon and lowland area in a short time period during which the inlet cross sectional areas do not provide enough capability to discharge the flood water to the sea.

The maximum water level differences between the lagoon and the sea at Thuan An and Tu Hien are 2.47 m and 2.81 m, respectively. These produce extreme flow velocities in the inlets of 3.68 m/s and 2.01 m/s at Thuan An and Tu Hien, respectively. Although the water level difference at Tu Hien is higher but due to the fact that it is narrower, shallower, longer, and it has a larger resistance so flow velocity in this inlet is still weaker. After the flood, the maximum flow velocities in the inlets diminish significantly to the normal values of less than 0.5 m/s as can be seen in Figures 7 and 8.

The high water level also exceeds the crest level of the sand barrier at the weakest point at Hoa Duan which is only approximately 2 m (above MSL) and 170 m wide. The overflow on the sand barrier at Hoa Duan can explain the breaching which occurred at this location in early November 1999. The maximum flow velocity through the opening at Hoa Duan can reach 4.25 m/s (Figure 7). High speed flow velocities scour the inlet channels tremendously. Although the beach at this location was eroded during the tropical storm Eve 10 days before, these model results show that not the typhoon but the river flood was the main cause for the breaching.

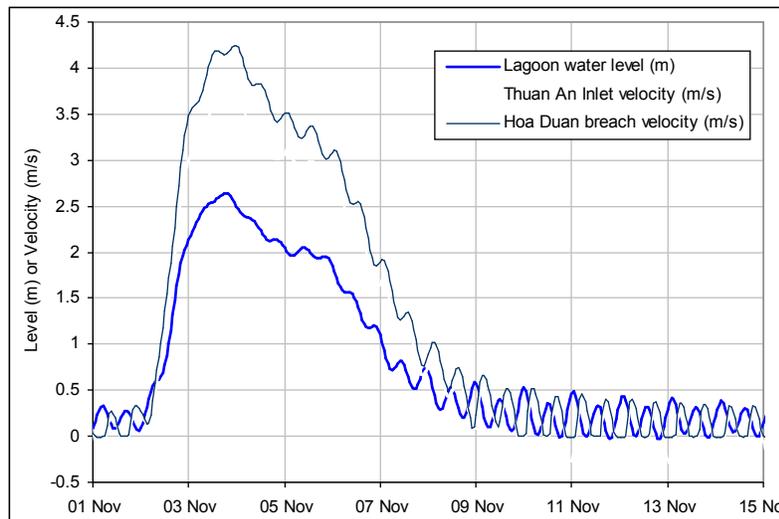


Figure 7: Computed lagoon water level and inlet flow velocities at Thuan An and Hoa Duan

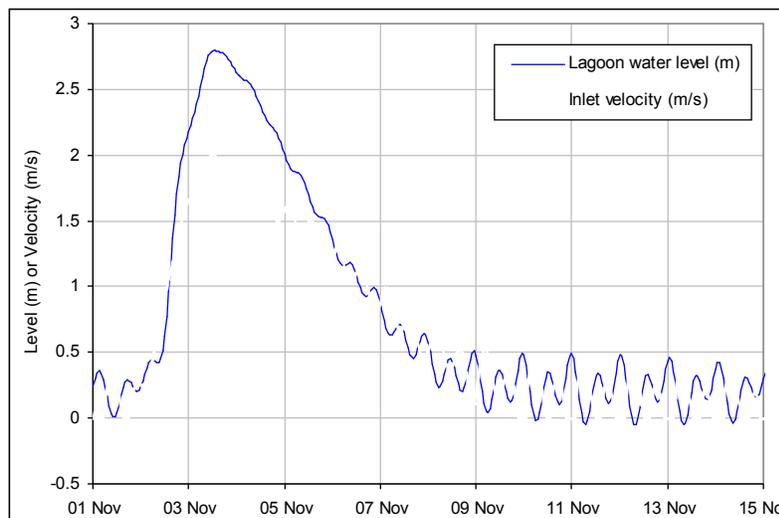


Figure 8: Computed lagoon water level and inlet flow velocity at Tu Hien

The maximum flow discharge through the Thuan An inlet can reach 14600 m<sup>3</sup>/s while the values at Hoa Duan and Tu Hien are 7800 m<sup>3</sup>/s and 2300 m<sup>3</sup>/s, respectively. Hence, the distribution of the flood peaks for Thuan An, Hoa Duan and Tu Hien is 59.1%, 31.6% and 9.3%, respectively, making Thuan An the main opening for flood water discharging.

*b) Tidal inlet morphological change in the flood of November 1999*

Figure 9 presents the simulated flow velocity field in the Thuan An inlet during the historical flood of November 1999. Inside the lagoon and in the inlet, flow concentrated as a high speed flow jet that scoured the channel. The direction of flood flow in the channels is rather stable during the flood. Only the magnitudes of flow velocities are varying in time. On the ebb tidal delta, river flood currents are still so strong and spread over the ebb tidal delta. Outside the ebb tidal delta, the river flood currents interact with ocean tidal currents in the along shore direction and create eddies depending on the rising or lowering phases of the tides.

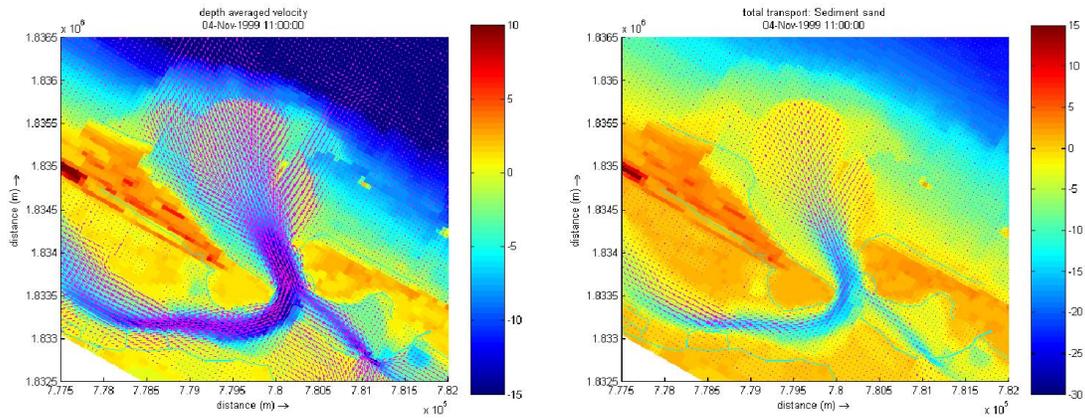


Figure 9: Flow velocity (left) and sediment transport (right) fields in Thuan An inlet during the flood of November 1999

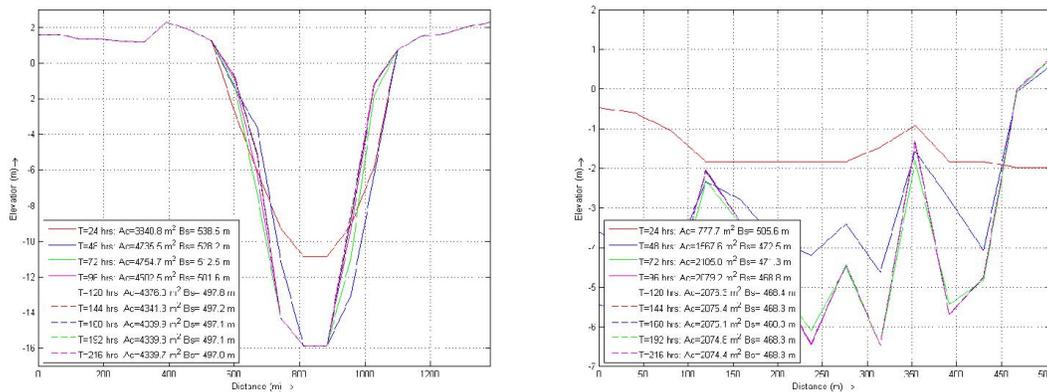


Figure 10: Channel cross section changes at Thuan An (left) and Tu Hien (right) inlets during the flood of November 1999

The sediment transport during the flood is also corresponding with the flow velocity as can be seen in Figure 9. Strong river flood currents erode the channel severely. Sediment is removed mainly from the channel and the ebb tidal delta and transported to the terminal lobe of the ebb delta where the flow velocities of river floods decrease significantly.

Figure 10 presents the changes in cross sections of the Thuan An and Tu Hien inlets during the flood of November 1999 including the variation in time of the cross sectional areas and surface widths. The changes of Thuan An inlet channel cross sectional area and depth have a good agreement with the bathymetric data surveyed. As observed in Figure 10, the Thuan An inlet channel was scoured by strong flow velocities of the flood in November 1999 and was deepened from a bottom level of -11 m to a deeper level of -16 m just within 48 hours of the peak flow period. Figure 10 also shows the shifting of the inlet channel to the right (southward). It does not like the migration of a meandering river which has the tendency of becoming more meandering due to the erosion of the concave bank and the accretion on the convex bank, the shifting of the Thuan An inlet during the flood of November 1999 has an opposite direction, i.e., its convex side eroded while its concave side accreted. This may be the mechanism of inlet channel reorientation which is shown in Figure 12 and will be discussed later.

When the river flow diminishes, because the inlet cross sections are scoured and become too large, the currents in the inlets drop significantly. For instance, the magnitudes of flow currents in the inlets reduce to less than 0.5 m/s just after the flood of November 1999 (Figures 7 and 8). With this value, currents in the inlets are unable to flush out the sediment deposited in the inlets. There is almost no sediment transported from the inlets into the lagoons and therefore, the flood tidal deltas can not develop.

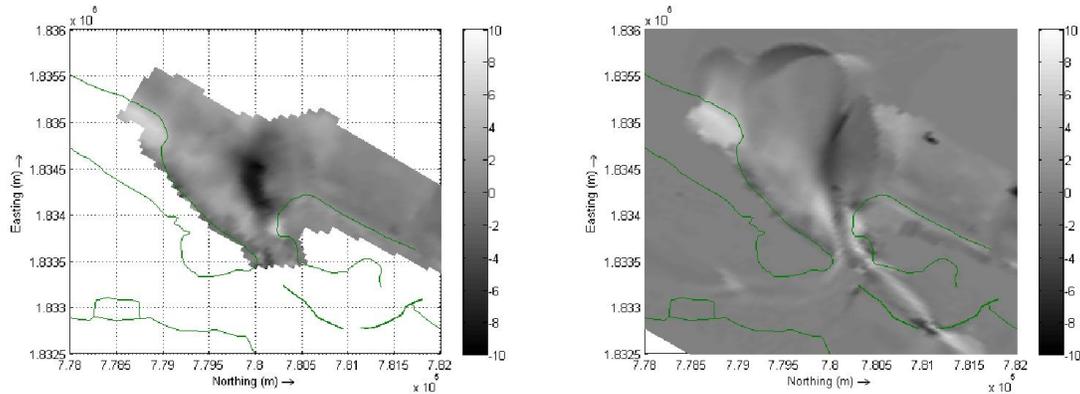


Figure 11: Bottom changes at Thuan An inlet from 1999-2002 surveys (left) and simulation (right)

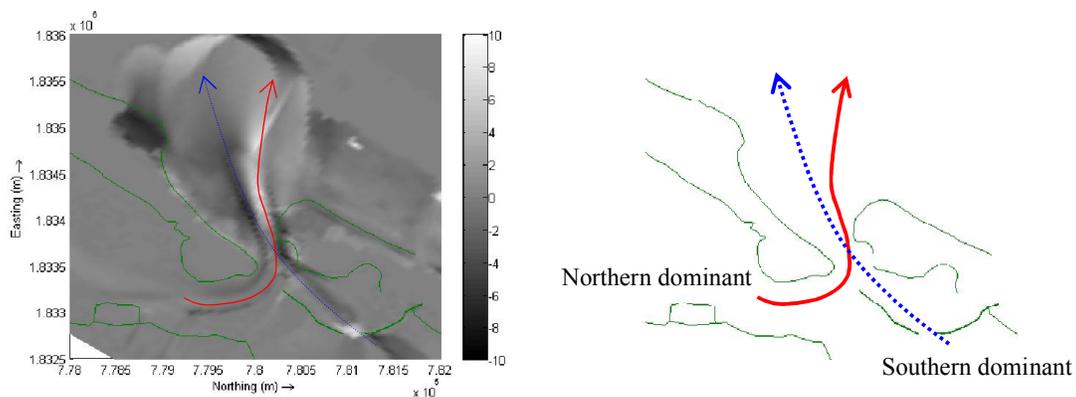


Figure 12: Influence of river floods on Thuan An channel orientation

Figure 11 shows the bottom changes at the Thuan An inlet made by the flood of November 1999 as simulated in the model and from survey data in 1999 and 2002. The erosion/deposition pattern in the inlet channel and on the ebb tidal delta from the simulation result and surveys are very similar.

Several computational scenarios have been conducted for different distributions of flood water from the rivers. Figure 12 shows the erosion/deposition pattern caused by two distinct scenarios: a) one with most of the flood water coming from the rivers on the north side of the Thuan An inlet (northern dominant); and b) one with most of the flood water coming from rivers south of the inlet (southern dominant). It shows clearly that the direction of the inner inlet channel depends on the side from which the dominant river flood discharge comes. If the flood water flows dominantly from the southern side of the inlet, i.e. contributed mainly by the rainfall in the Huong River catchment, the flood flow will reorient the inlet channel to northwest direction as the same as its direction. If the flood water coming from the northern side is stronger (that is caused by much rainfall on

the northern catchments of the O Lau and Bo rivers) then the dominant flow direction has a tendency of becoming perpendicular to the coast that turns the inlet channel to the northeast direction.

#### **4. Conclusions**

In this study, hydrodynamics and morphodynamics of the Thuan An and Tu Hien inlets have been simulated and analyzed. Hydrodynamics and morphodynamics of the inlets are shown to be strongly influenced by the monsoon regime which is reflected by the seasonal variations of river flow, wave climate and sediment transport patterns. The inlets are alternately controlled by river flows in the flood season and ocean waves in the remaining period of a year. Tidal forcing is subjugated by the river flow and wave action and is relatively weak for sediment flushing. Sediment which enters the inlet channel by littoral drift is hardly transported by tidal currents out of the inlet neither in seaward direction to the ebb tidal delta nor in landward direction to the lagoon to build up the flood tidal delta.

Most of the sediment transported by the rivers through the inlet in the flood season. River floods not only transport fluvial sediment but also scour the inlet channels to increase inlet cross sections. River floods do not only deepen the inlets by their strong currents but they can also reorient the inner inlet channel depending on the direction of the dominant flow and can create new inlets by breaching the sand barrier due to high rising flood water level. In the end of winter from January through March, 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. These may be the cause of shoreline erosion at the adjacent coasts at both sides of the inlets, especially the updrift coasts on the northern sand barriers of the inlets.

Small waves and swell in the summer months rework partly the sediment transported offshore by river floods and transport it back 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. Due to the prevailing net longshore sediment transport in the Thuan An inlet area, the southern sand spit of the inlet grows to NW direction.

The difference in longshore sediment transport at both sides of the Tu Hien inlet due to the southern coast is sheltered from a portion of wave action by the headlands at Loc Thuy and Cape of Chan May Tay indicates the closure of the Tu Hien inlet by sediment transported from its north coast.

#### **References**

- Bijker, E.W., 1971. Longshore Transport Computations. *Journal of the Waterways, Harbours and Coast Engineering Division*, 97(WW4): 687-701.
- Hoi, T.D., Cu, N.V. and Phu, H.N., 2001. Synthesis report "Rehabilitative and adaptive alternatives for the coastal area from Thuan An to Tu Hien and the Tam Giang-Cau Hai lagoon system", Hanoi.
- Van Rijn, L.C., 1984a. Sediment Transport, Part I: Bed load transport. *Journal of Hydraulic Engineering*(10).
- Van Rijn, L.C., 1984b. Sediment transport, Part II: Suspended Load Transport. *Journal of Hydraulic Engineering*, 11.
- WL | Delft Hydraulics, 2001. SOBEK - Technical Reference, WL | Delft Hydraulics, Delft.
- WL | Delft Hydraulics, 2006a. Delft3D-FLOW User Manual Version 3.13, Delft.
- WL | Delft Hydraulics, 2006b. Delft3D-WAVE User Manual Version 3.02, Delft.