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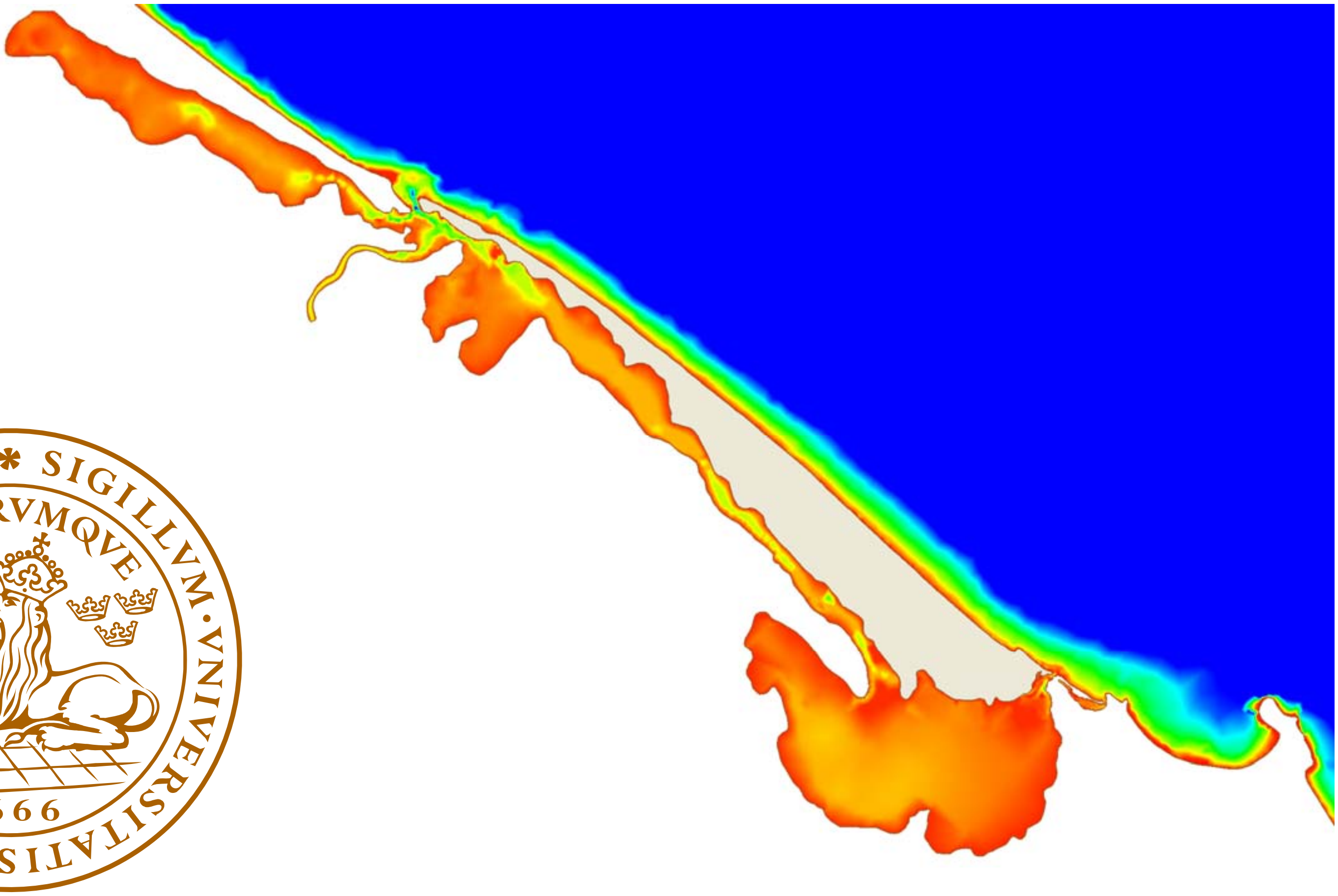
An Investigation of Exchange Rates in the Tam Giang-Cau Hai Lagoon System, Vietnam, through Hydrodynamic Modeling

Michael C. Tushaj



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Abstract

The Tam Giang-Cau Hai lagoon system, two inter-connected and naturally occurring coastal lagoons located in the Thua Thien-Hue province of Vietnam, comprises two inlets: Thuan An and Tu Hien. The Thuan An and Tu Hien inlets connect the lagoon system to the South China Sea and they are subjected to morphologic changes due to sediment transport effects. The magnitude of sediment transport is determined by wave breaking and long-shore currents as well as by the abundance of sediment found along the sandy coastline. Variation in the coastal sediment transport, as well as in tidal and river flows at different temporal scales significantly affect inlet geometry; a direct result being either a marked widening or narrowing of the inlets, features which are highly seasonally dependent and that also lead to inlet migration and closure. The water exchange between the lagoon and the sea is mainly influenced by the tide, however, the river flow could also affect the exchange during certain times of the year, although this has not been studied in detail in the present investigation. During the end of the winter monsoon season, inlet morphology is dominated by wave action and strong sediment deposition that can lead to a complete closure of the southern inlet of Tu Hien, subsequently creating a new inlet by means of sand spit breaching, approximately 3 km south at Loc Thuy. Inlet closure of lagoons creates unfavorable conditions for water exchange between the lagoon and the sea which can deteriorate water quality and destroy the aquatic ecosystem.

This report investigates the conditions controlling the migration and morphology of the inlets with focus on the impact on the water exchange with the South China Sea. Simulations were carried out of the water circulation in the lagoon and how the lagoon exchanges its water with the sea using the ADCIRC model within the Surface Modeling System (SMS) software. This regional model for tidal circulation was used to determine water surface elevation and velocities for the lagoon system using LeProvost global tidal forcing along the ocean boundary of the model. Based on the simulated velocities, exchange rates between the lagoon and the sea were calculated for particular situations.

The simulations performed in this study demonstrate that the northern inlet at Thuan An is most important for the water exchange between the lagoon system and the sea; however, the Tu Hien inlet in the south is more susceptible to morphologic changes. Although the Thuan An inlet overall dominates the water exchange between the lagoon system and the sea, the water exchange at Tu Hien inlet is crucial for the southern lagoon (Cau Hai). As Tu Hien inlet closes, the amount of water exchanged between the entire lagoon system and the sea decreases because the Thuan An inlet to the north cannot sufficiently account for the loss of water exchange through a completely closed Tu Hien inlet.

Preface

The results of this dissertation were mainly due to data obtained from a combined field study and computer modeling effort focusing on the local hydrodynamics of the Tam Giang-Cau Hai lagoon system. The main purpose of the thesis was to further increase our understanding of how sedimentation at lagoon inlets, including their related migration, may affect lagoon circulation and water exchange by investigating the Tam Giang-Cau Hai lagoon system located in central Vietnam. In-depth analysis of this lagoon system will lead to a better understanding of the effects inlet sedimentation, migration, and closure may have on lagoon water quality. This task was completed through the Division of Water Resources Engineering (WRE) at Lund University with collaborative help from the Institute of Mechanics in Hanoi, Vietnam.

Acknowledgements

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1 Introduction

1.1 Background

Coastal lagoons are defined as inland bodies of water that are separated from the ocean by a barrier, which is frequently a naturally occurring land barrier, and have one or more connections to the sea through inlets (Kjerfve and Magill, 1989). These water bodies occur along areas with lowered elevations at or around sea level and are often found along the shorelines of coastal land masses. In comparison to other water bodies, information on processes related to coastal lagoons is limited; however their existence is seen widely throughout the world, occurring on about 13% of all coastlines in the world (Kjerfve and Magill, 1989)

Most coastal lagoons were created after the Holocene sea level rise stabilized nearly 5,000 years ago, which resulted in a rapid rising of sea water levels by approximately 130 meters. Subsequent longshore sedimentation played a large role in the formation of coastal lagoons; building land barriers that choked water exchange to the ocean and diminishing their ability to flush out pollutants by largely increasing residence time within the lagoon (Kjerfve and Magill, 1989). These formations are ephemeral on a geologic scale; however, they are of great use while they exist to their surrounding inhabitants, creating navigational pathways as well as sources for water exchange and pollution dispersal into the ocean. Recurring longshore sediment transport threatens to disrupt the balance of coastal lagoons, creating an overabundance of sedimentation at lagoon inlets due to tide, wind, and wave action against the coast.

The Tam Giang-Cau Hai lagoon system is a naturally occurring lagoon system located along the eastern coast of central Vietnam, near the city of Hue. It has two inlets, Thuan An in the north and Tu Hien in the south part of the lagoon system (see Figure 1). During different seasons and under different conditions of sediment transport, the southern inlet at Tu Hien can become completely filled with deposited sediment, in which case another inlet forms naturally about 3km south at Loc Thuy (Lam *et al.*, 2007a). Coastal processes in conjunction with prevailing climatic conditions control the morphology of the lagoon inlets at Thuan An and Tu Hien, as well as their migration along the coast. Because little is known about coastal lagoons, it is important to study the effect of climate and coastal processes on both the exchange of water between the lagoon and sea as well as the migration of the inlets themselves. Coastal processes, such as inlet sedimentation and scouring, can be attributed to the growing problems of water exchange within the lagoon, increasing the turbidity of the water and subsequently degrading the water quality, circulation and exchange as well as the conditions needed to sustain aquatic life. Pollution from human activities also plays a large role in the overall lowering of lagoon water quality and increased levels of pollution. Gaining a further understanding of the inter-relationship between these processes and the lagoon will decrease the cost and effort in maintaining a viable lagoon system with satisfactory conditions for the aquatic life.

In order to better understand the aspects of water exchange within the lagoon, it is useful to determine the amount of time it takes for a certain volume of water to be flushed out of the lagoon system, better known as the lagoon renewal time. Equally important are the determining factors that directly influence the water exchange process, namely winds, tides, and river flows, as well as the natural geometry of the lagoon and its inlets. Properties related to the lagoon renewal time can be estimated through the analysis of the tide and river conditions as well as prevailing wind conditions that help to force internal circulation.

1.2 Objectives

The main objectives of this study were to:

- Investigate the physical processes governing inlet migration and closure at the Tam Giang-Cau Hai lagoon system in Vietnam
- Apply a mathematical model to describe the impact of the inlet migration and closure with respect to water exchange between the lagoon system and the sea with focus on the tidal forcing
- Qualitatively assess the effects of a modified water exchange on the environmental conditions within the lagoon system

1.3 Procedure

A comprehensive literature review including books, journals, articles, online media, and unpublished works was undertaken in order to gain adequate knowledge about the relevant physical processes to understand the coastal lagoon system at Tam Giang-Cau Hai in Vietnam. The review focused on such coastal processes as water exchange and inlet migration with respect to climate, sedimentation and geography, both in a general sense as well as to what applies specifically to the target area in Vietnam. Since information about coastal lagoons is limited, knowledge from estuaries was employed in some cases (Kjerfve and Magill, 1989).

Understanding of the coastal processes governing the Tam Giang-Cau Hai lagoon system was further developed through an intensive field study in the target area. The field study was undertaken in the cities of Hanoi and Hue for approximately one month, in which measurements and data collection were carried out. A thorough review and compilation of relevant literature regarding the inlets of the Tam Giang-Cau Hai lagoon system were performed at the Center for Marine Environment Survey, Research, and Consultation (CMESRC), Institute of Mechanics in Hanoi. Also, several data sets and simulation results originating from previous field experiments and various other studies were obtained.

Specific measurements of inlet depth and water velocity were carried out on site of the lagoon system near the city of Hue with the help of different hydrodynamic measuring instruments (*e.g.*, DNC-2M and OBS-3A). Measurements of the wave climate were also undertaken using these instruments. Compilation of measured data provided by Vietnamese researchers at the Institute of Mechanics, including coastline positions and bathymetrical data, were used as input to the Surface water Modeling System (SMS) software in order to calculate velocities and water surface elevations in the lagoon system. The main program utilized in the SMS was the tidal circulation model ADCIRC, which uses the governing hydrodynamic equations in two horizontal dimensions to simulate flow velocities on a regional scale based on tidal input at the boundaries. A major focus of the literature review, data collection, and model simulation was the southern inlet of the lagoon at Tu Hien, since it has been observed to be more prone to inlet migration and morphological change than the northern one at Thuan An.

2 Study Area

2.1 General

The Tam Giang-Cau Hai lagoon system lies in the Thua Thien-Hue (TT-Hue) province along the coast of central Vietnam, located between16°00' – 16°45' North Latitude and 107°03' - 108°12' East Longitude. The province itself has a surface area of about 5,000 km^2 with a population encompassing over 1 million. Its coastline has a length of approximately 126 km (Hung *et al.,* 2007). The lagoon system itself stretches a total distance of about 68 km (Lam, 2002), and it is notably the most important lagoon system in Vietnam and the largest in all of Southeast Asia. The total surface area of the lagoon system is about 220 km^2 (Lam *et al.*, 2007b), sustaining life to approximately 300,000 surrounding inhabitants (Lam *et al.*, 2007a).

The Tam Gaing-Cau Hai lagoon system receives water from a drainage basin of roughly 4,000 km^2, a contribution heavily dependent on the various connecting river flows into the lagoon (Lam *et al.*, 2007a). The lagoon system is feed by several rivers, two of which are most important during the flood months, the Huong (Perfume) river and the O Lau river. Of the 4,000 km^2 basin that generates runoff to the lagoon, 2623 km^2 and 745 km^2 are contributed from the Huong and O Lau rivers, respectively (Lam *et al.*, 2007a). During the flood season the lagoon receives a large amount of water directly as river channel flow and indirectly as inundated coastal runoff.

The lagoon system is heavily relied upon for its importance as a means of navigation, fishing, aquaculture and agriculture, as well as a relief for coastal inundation (Lam *et al.*, 2007a). This large lagoon system is also home to several different species of life, including an estimated 21 different species of local birds that are protected by European and Vietnamese legislation. This combined lagoon system is also home to many species of aquatic animals, with about 200 different species of fish, including a large shrimping industry which helps relieve much economic burden for the surrounding inhabitants (Du Lich Online, 2009).

This important aquatic system is in principal comprised of two different lagoons (Tam Giang lagoon and Cau Hai lagoon) connected by a narrow strip of water at Thuy Tu, as seen in Figure 1, with limited water exchange between the lagoons.

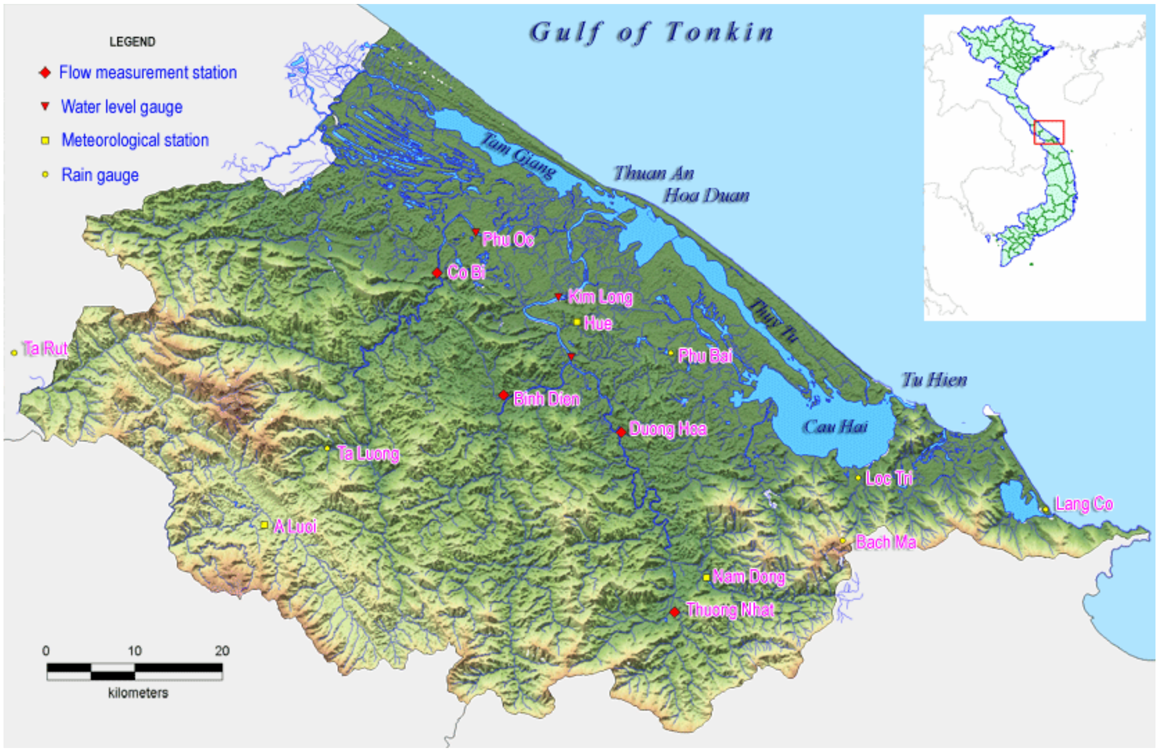


Figure 1 Map of Tam Giang-Cau Hai lagoon system and surrounding areas (Lam *et al.*, 2007a)

2.1.1 Tam Giang Lagoon

The Tam Giang lagoon, located at 16°32'-16°39'N, 107°26'-107°37'E in the northern part of the Tam Giang-Cau Hai lagoon system, is approximately 10 km north of the city of Hue. It connects the fresh water of the lagoon system to the southern boundary of the Gulf of Tonkin through an inlet at Thuan An. During extreme events when the Thuan An inlet closes, water may exit the lagoon through an inlet formed at Hoa Duan, slightly southeast of Thuan An. Tam Giang lagoon is relatively large, comprising about 20 km in length with a maximum with of 3km and it covers an area of about 7,800 ha (Le D.D., 2009). The Tam Giang lagoon is the junction point of six Vietnamese rivers, the O Loan, Bo, Huong, Truoi, Dap Dinh, Thien Hon, and Cong Quan rivers, allowing for large seasonal inflows of river water to the lagoon during the North East monsoon rains. A comprehensive study focusing on the importance of these river flows on the migration of both the Thuan An and Tu Hien inlets has not yet been performed, however the flows should be important for the migration of the inlets during the rainy season. The mean depth of the lagoon is approximately 1.3 meters (according to depths interpolated from several actual lagoon depth charts) and the composition of the water is brackish with an equivalent salinity content of 1.66% to 2.18% (16.6-21.8 parts per thousand (ppt); Le D.D., 2009). Figure 2 shows a more detailed depiction of the lagoon via satellite photo, whereas Figure 3 shows the general bathymetry observed in this lagoon (also used in the ADCIRC model simulations).

Figure 2 Satellite image of the Tam Giang lagoon (Crisp National University of Singapore, 2009)

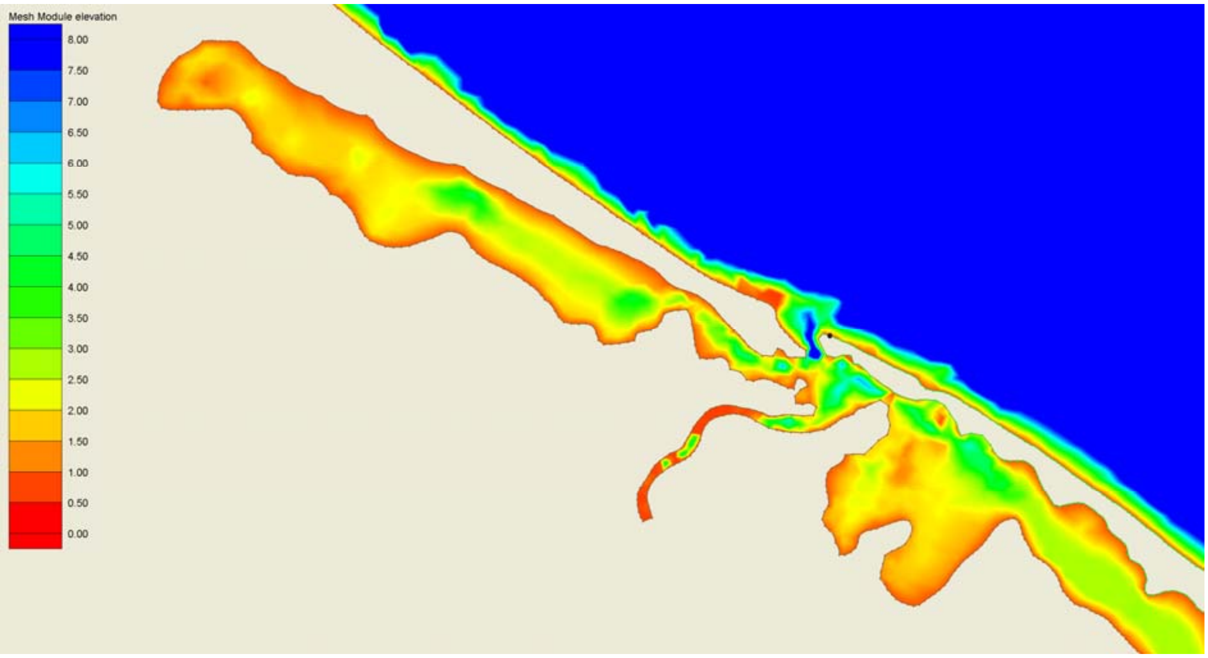


Figure 3 Bathymetry of Tam Giang lagoon (from the ADCIRC model simulations)

2.1.2 Cau Hai Lagoon

The Cau Hai lagoon, located around 16.23°N, 107.97°E in the southern half of the Tam Giang-Cau Hai lagoon system (Cau Hai Lagoon, 2009), is the more important of the two inter-connected lagoons with respect to variations in the hydrodynamics and inlet morphology. It is regularly exhibiting poor water exchange for several reasons including its specific climate and geographic location. The dual climatic forcing observed in this area present different water exchange and general hydrodynamic conditions, which have dramatic effects on the development of Tu Hien inlet morphology during the year. The difference in elevation between the northern lagoon at Tam Giang and the southern Cau Hai lagoon prevents any proportional water exchange between the two lagoons. The large distance of separation between the lagoons through the thin connecting strip of water at Thuy Tu also limits water exchange between the two lagoons.

The Cau Hai lagoon itself (Figures 4 and 5) covers a surface area of approximately 11,200 ha (112 km^2), roughly one and a half times larger than the northern lagoon of Tam Giang (Wikimapia.org, 2009). The interpolated depths inside of the lagoon were within the range of a few meters, with a mean water depth of 1.0 meters throughout the lagoon and a depth of approximately 1.8 meters inside of the inlet. Measurements of the salinity content and temperature were recorded using a OBS-3A measuring system. A visual of the salt water intrusion from the sea into the lagoon can be seen in Figure 23 as photographed during the field campaign at the lagoon in late February 2009.

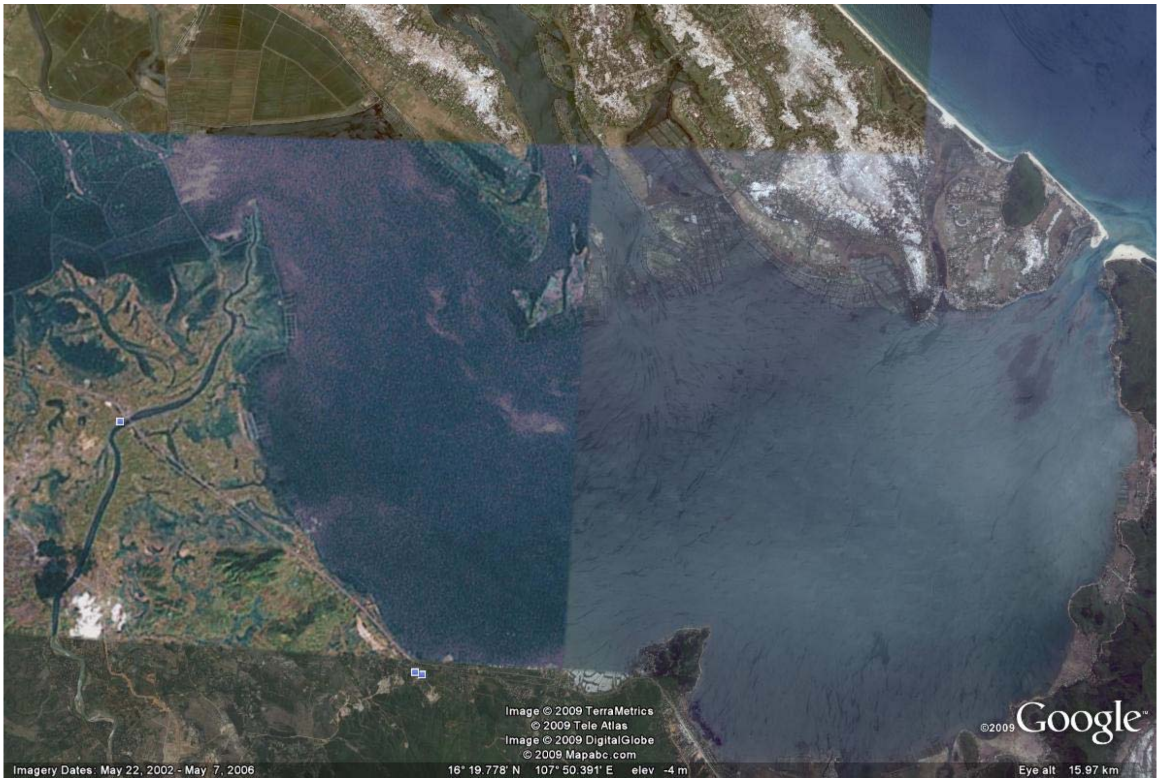


Figure 4 Satellite image of Cau Hai lagoon (Google Earth, 2009)

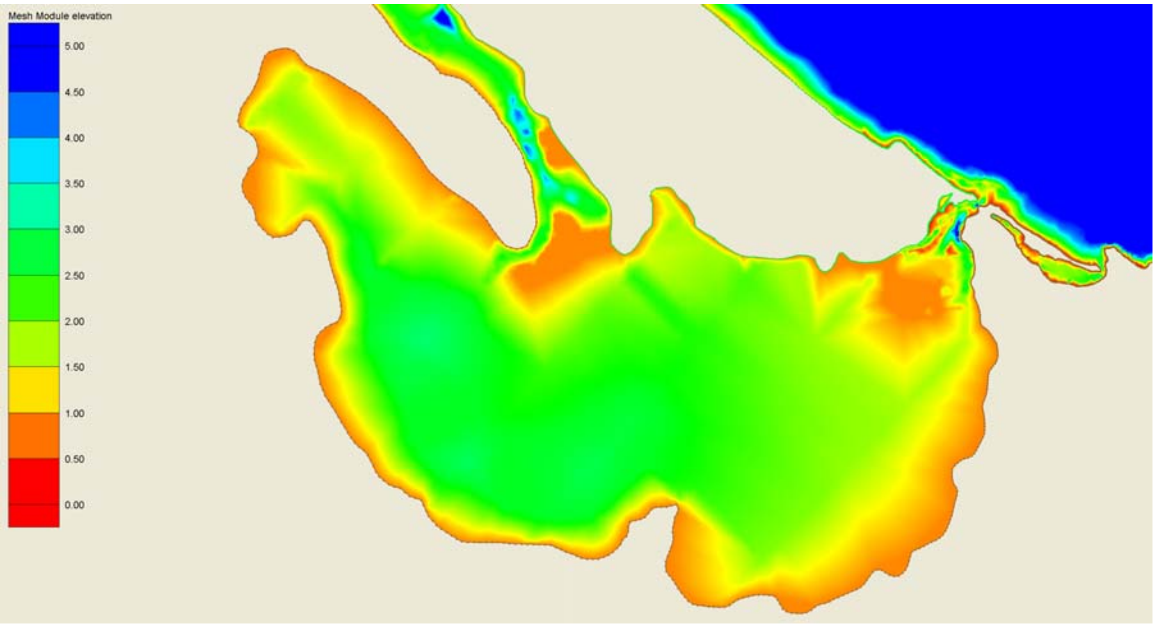


Figure 5 Bathymetry of Cau Hai lagoon (from the ADCIRC model simulations)

2.2 Climate

The Tam Giang-Cau Hai lagoon system is located in central Vietnam and is influenced by a tropical monsoonal climate incurred by a West Pacific Typhoon regime (Tran et *al.,* 2008). Specific wind and wave climates determine the coastal processes observed in the region. The West Pacific Typhoon regime provides central Vietnam with substantial amounts of rainfall, which in turn increases climate-induced problems such as coastal erosion and inundation, which mainly originates from tropical storms and cyclones (Tran et *al.,* 2008). The area around the lagoon system receives approximately five tropical cyclones every year during the period from June to November; a climatic pattern that is responsible for over 80% of the flooding events in the area, according to statistical data (Tuan, 2007).

2.2.1 Temperature and Humidity

The average annual temperature and humidity of the Hue region is 25 °C and 83% respectively (Lam, 2002). Values of these parameters change in accordance with the season; average values of temperature range from 19.7 °C in January to 29 °C in June with maximum and minimum temperatures reaching as high as 40.7 °C and as low as 10.2 °C, respectively (Tung, 2001). The relative humidity of the region fluctuates between 72% in July to 89% in December to February (Tung, 2001).

2.2.2 Effects of Changes in the Climate

Changes in the climate largely affect coastal conditions and inlet morphologies of the lagoon system. Inlet stability in the Tam Giang-Cau Hai lagoon system, mainly at the Tu Hien inlet, is poor on average due to effects caused by the duality of the seasons. The NE Monsoon lasts only for a couple of months each year, but has a crucial role concerning inlet stability; large amounts of runoff from precipitation are discharged into the lagoon, widening the inlet as well as increasing the potential for breaching that may occur through the land barrier separating the lagoon from the South China Sea (Tuan, 2007). More analysis of the effect of river runoff is provided in section 2.2.4.

2.2.3 Precipitation

Measurements of precipitation during the South West and North East Monsoon seasons average around 25mm (March) to 740mm (October) of precipitation, respectively, as measured at the Hue rainfall station (Tung, 2001). At the Ta Trach rainfall station, located upstream where the Ta Trach river helps form the Perfume river, mean precipitation values are lower, ranging from 30mm (February) to 530mm (November) (Tung, 2001). The average annual rainfall measured at Hue station is 2470mm, which is heavily dependent on the occurrence of tropical storms that increase the intensity and duration of the precipitation. The amount of days per month which receive rainfall follow a seasonal trend; average occurrences of rainfall are measured to be approximately 8 days in April and 20 days in November (Tung, 2001).

During the rest of the year lowered lagoon water levels, due to lowered precipitation, lowered river runoff, and increased evaporation rates (Lam, 2002) contribute to deteriorate inlet stability (Lam *et al.*, 2007a). Since inlet stability is dependent on seasonal precipitation, it is useful to investigate the relationship between inlet morphology and climate based on the precipitation data. Figure 6 shows the long-term trend between precipitation and each of the climatic seasons with respect to time. The trend shown in figure 6b seems most conclusive: a decreasing average monthly precipitation during the dry season allows waves to control inlet morphology more dominantly together with the tide compared to river runoff. Thus, with the progression of time, inlet stability may be more difficult to maintain and could lead to more frequent inlet closure in the future.

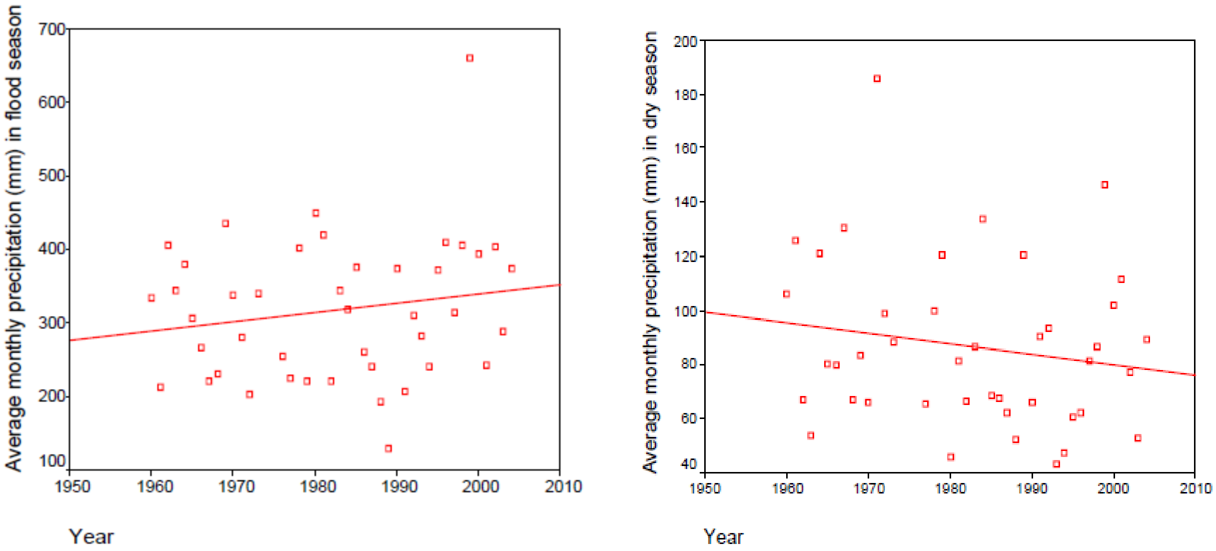

(6a) **(6b)**

Figure 6 Precipitation distribution during both the (6a) NE Monsoon Season and (6b) SW Monsoon Season in the Thua Thien Hue Province of Central Vietnam (Tran *et al.*, 2008)

The location of the Tam Giang-Cau Hai lagoon system makes it vulnerable to attack by seasonal tropical storms. Approximately 10 typhoons arrive from the South China Sea yearly. On average, the coast of Vietnam will annually receive between 4 and 6 of these typhoons (Larson *et al*., 2006); however, it has been regularly observed that as many as 10 typhoons may reach the coast during a single year (Tung, 2001). Due to the shape and position of the Vietnamese coastline, most typhoons affect the north and central regions; however, approximately 60% of the country's population (43% of the entire country area) is influenced by the effects of typhoons (Tung, 2001). The impact of typhoons can be observed through inspection of precipitation data. Also, they create storm surges measured to be typically about 1m in height. Approximately 30% of all storm surges produce a water level increase of 1.5m and on rare occasions up to 2.5m (Tung, 2001). These surges are detrimental to the stability of the inlets and may greatly affect the water exchange between the lagoon system and the South China Sea.

2.2.4 Wind Climate

Winds occurring in the TT-Hue province of Vietnam follow a seasonal pattern coinciding with the wet and the dry season. In general, increased internal lagoon water circulation may be directly related to increased wind strength, where a decrease in the water depth also promotes increased circulation. Both the morphology and the migration of the Thuan An and Tu Hien inlets are partly governed by the two dominating seasonal climates, the winter (North East) monsoon season and the summer (South West) monsoon season. North east winds during the winter monsoon season dispense heavy precipitation on the Truong Son mountain range in central Vietnam, creating a large influx of water flow from land into the Tam Giang-Cau Hai lagoon system (Lam *et al*., 2007a). This wet season lasts from about Mid October until roughly the end of February, when the dry season dominates implying a changing wind direction from North East to South East. The warmer Southeasterly winds of the summer monsoon last for the remainder of the year. Changes in water circulation within the lagoon because of decreased lagoon water depths due to lowered river flow input and increased evapotranspiration become apparent.

During the SW monsoon season, inlet morphology is dominated mainly by tidal variation (Lam *et al*., 2007a). Wind climate follows the dual seasonal trend for each subsequent year with only occasional interruption in the SW monsoonal wind direction by the formation of tropical storms with North Eastern origin, which frequent the coast of Hue (Tuan, 2007). However, observation yields that the highest probability of these storms occurring is in the North Eastern monsoon season between the months of November and December (Hung *et al.* 2007).

2.3 Wave Climate

The wave climate experienced in the coastal area along the Tam Giang-Cau Hai lagoon system is affected by the biyearly wind pattern originating from the NE and SW Monsoons. The NE Monsoon creates incident waves that travel along a Southwest path from Southern China, ultimately breaking with almost normal incidence against the central coastline of Vietnam (Lam, 2002). The average significant wave height (H_{Sig0}) measured during the present field study was 0.55 m and the peak spectral period was 9.4 sec. These values were based on individual measurement records of water level, each comprising 15 minutes of data, during a total time period of about two days.

The SW Monsoon emerges in the summer months from the southeast, making its way around the southern tip of Vietnam. The characteristics of the wave climate are the same as for the monsoon winds arriving from the South East (Lam, 2002). It is important to note that due to the orientation of the coastline near the Tu Hien inlet, waves break at near normal incidence along the shoreline outside the lagoon after they have been diffracted and refracted in the offshore area. North of the Tu Hien inlet, however, the shoreline orientation implies that wave conditions from the southeast create moderately strong longshore currents, which drives a longshore sediment transport in the northwest direction up the coast.

2.4 Tidal Climate

The Tam Giang-Cau Hai lagoon system is situated in a microtidal area with a tidal range less than 0.5 meters (Lam, 2002), implying that morphodynamically the inlets exhibit a strong dependence on the waves. The tidal range increases southward from the Thuan An inlet to the Tu Hien inlet, with values reaching between 0.3 – 0.6 m at Thuan An and 0.55 – 1.0 m at Tu Hien inlet, respectively (Lam, 2002). Along the entire 70km stretch of the connected lagoon system, however, there is a slight change in the tidal conditions. The southern inlet of Tu Hien experiences a mixed tidal regime comprised of a dominant semi-diurnal signal, whereas the northern inlet at Thuan An experiences a fully semi-diurnal tidal regime. Tidal currents at the inlets decrease in the seaward direction with the increased water depth. Observation of tidal currents at the Thuan An inlet have yielded values between 0.25 – 0.3 m/s in water depths of 10 – 15 meters (Lam, 2002).

2.5 River Flows

As indicated by Lam (2002) in his site investigation of the Tam Giang-Cau Hai lagoon system and its hydrodynamics, all of the rivers within the surrounding area, except for the Xe Xap River, discharge either directly or indirectly into the combined lagoon system. The major rivers include the O Lau River, the Dai Giang River, the Cau Hai River, the Nong River, the Truoi River, and most noticeably the Huong River (Lam, 2002). There are conflicting studies on the importance of the river effects on the water exchange between the lagoon system and the South China Sea; however, consideration of the relatively large catchment area (approximately 4000 km^2; Lam, 2002), in combination with a simple mass balance, would indicate a significant influence of river flow on the hydrodynamic processes within the lagoon, including the water exchange, during the rainy season. Detailed analysis of all of the aforementioned rivers would provide a better basis for assessing the actual effects on the water exchange; however, the main river of importance should be the Huong River. This river receives water from about 75% of the combined catchment area (Lam, 2002).

2.6 Lagoon Water Level Variations

Variations in lagoon water level exhibit seasonal behavior corresponding to the NE and SW Monsoons and the amount of river runoff that is discharged into the lagoon (Lam *et al.*, 2007a). Due to the difference in precipitation and temperature during these two seasons, lagoon water levels vary moderately. Seasonal variations in water level have also been theoretically linked to variations in input from river discharge. The NE Monsoon brings large quantities of rainfall, which cause the lagoon water level to rise. The rise of lagoon water levels, causing increased outflow to the sea, has been proposed to induce inlet scouring and ultimately widen the inlet mouths (Lam *et al.*, 2007a). Effects from the SW Monsoon season imply an overall lowering of lagoon water levels due to decreased river runoff into the lagoon as well as increased evaporation rates generated by the warming South Easterly winds. Thus, the rise and fall of lagoon water levels follow a seasonal cycle in accordance with the monsoons, and this cycle is important for determining environmental as well as ecological conditions in the lagoon.

2.7 Sediment Transport Patterns

According to Lam (2002) in his preliminary study on the hydrodynamics of Tam Giang-Cau Hai lagoon system, net longshore sediment transport is in the NW and SE directions for the Summer and Winter seasons, respectively, along the coastline adjacent to the two inlets. The measured velocities of the longshore currents are in the range 0.3-1 m/s (Lam, 2002). The long straight coastline between the inlets is affected by the open sea and here the longshore currents are moderate; however, during the SW Monsoon the situation at the Tu Hien inlet is markedly influenced by wave refraction and diffraction because of the presence of a land barrier to the south. Observations of the nearshore wave direction at the mouth of the inlet during summer conditions indicate a near normal incidence of the waves towards the coastline, which decreases the NW flow of sediment away from the mouth of Tu Hien.

2.7.1 Transport along the Coastline

The magnitude and direction of the transport of sediment along the coastline near the Tam Giang-Cau Hai lagoon system are direct functions of the nearshore wave conditions. Lam (2002) attributed the main driving force behind the sediment transport along the central coast of Vietnam to the wave-induced longshore currents. Problems associated with calculations of sediment transport rates arise from the inaccuracy of mathematical equations to simulate marine sediment transport, which is typically estimated to be accurate within one order of magnitude of the actual rates (Lam, 2002). Table 1 shows the estimated sediment transport rates along different locations of the shoreline outside the Tam Giang-Cau Hai lagoon system according to Lam (2002). Lam (2002) estimated the most reliable values on the total sediment transport for the Thuan An and Tu Hien inlets to be 1.6×10^6 and 1.2×10^6 m^3/year, respectively.

2.7.2 Transport through the Inlets

Annual transport of sediment from the lagoon system through each inlet differs dramatically for the two inlets and depend on the particular characteristics of the seasons. Based on observations, the sediment transport rate in the year 1993 and during the winter monsoon season of 1995 was estimated to be 144 tons/day from the sea into the lagoon during the dry season and 2,443 tons/day from the lagoon to the sea during the rainy season in the Thuan An inlet (Lam, 2002). The total annual sediment transport through the Thuan An inlet is estimated to be 259,000 tons/year into the sea, whereas only approximately 9,500 tons/year is transported out through the Tu Hien inlet (Lam, 2002). These values include both the sediment supply from river discharge and from the lagoon itself. Estimates of the transported sediment from the lagoon itself are difficult to make due to the complexity of the governing processes and the inaccuracy of computational equations for sediment transport rates. The main reason for the large differences in sediment transportation between the inlets is the effects of the large river discharge at Thuan An inlet during the rainy season, which contribute large flows of water mixed with sediment into the lagoon.

Table 1 Estimated sediment transport rates at various shoreline locations outside the Tam Giang-Cau Hai lagoon system based on different sediment transport modeling approaches (Lam, 2002)

Source and Year	Sediment Transport (m^3/year) and Direction	Net Sediment Transport (m^3/year) and Direction	Total Sediment Transport (m^3/year)	Location
VIWRR[1] 1999	$1.503x10^{6}$ NW	$1.44x10^{6}$ NW	$1.566x10^{6}$	Thuan An Inlet
	$0.063x10^{6}$ SE			Hoa Duan Inlet
CERC 1996	$1.41x10^{6}$ NW	$0.60x10^{6}$ SE	$3.42x10^{6}$	Thuan An Inlet
	$2.01x10^{6}$ SE			Hoa Duan Inlet
Lee[2] 1970	N/A	N/A	**$1.6x10^{6}$**	Thuan An Inlet
SEDTRAN 2001	$0.11x10^{6}$ NW	$0.43x10^{6}$ SE	$0.65x10^{6}$	TT-Hue Coastline
	$0.54x10^{6}$ SE			
UNIBEST 2001	N/A	$0.3x10^{6}$ NW	N/A	Thuan An Inlet
	N/A	$0.1x10^{6}$ NW	N/A	Hoa Duan Inlet
H.I.O.[3] 1993	$0.715x10^{6}$ SE	$0.220x10^{6}$ SE	**$1.210x10^{6}$**	Tu Hien Inlet
H.I.O.[3] 1995	$0.495x10^{6}$ NW			

1 Analysis done through the Vietnam Institute for Water Resources Research

2 Estimations done by Lee from annual sediment budget surveys, bathymetry changes and dredging studies in 1970.

3 Haiphong Institute of Oceanography survey and estimated results, 1993 and 1995.

Note: In table above calculated rates are based on different years.

3 Inlet Migration and Morphological Change

3.1 General

The Tam Giang-Cau Hai lagoon system lies within a micro-tidal regime (Thanh *et al.*, 2006), dominated by the wave conditions during the monsoon seasons, and it is therefore exposed to inlet migration and closure taking place over one or several seasons. The migration of coastal lagoon inlets can be detrimental to the social and economical conditions of the surrounding region. In the case of the Tam Giang-Cau Hai lagoon system, inlet migration causes economic hardships due to the high dependence upon the fishing industry as well as the importance of navigation to the open sea. Furthermore, negative impacts occur on the ecosystem and the environment of the lagoon: closure of the inlets changes lagoon salinity which affects the population and growth of prawn, which is the leading economic feature of the fishing industry in the lagoon (Lam, 2002).

3.2 Inlet Morphology Changes

3.2.1 Conceptual Model of Morphology Change

Dramatic morphological inlet changes typically occur during the NE Monsoon season, when large runoff from precipitation through the river discharge into the lagoon may scour the bank of the inlets. The Tu Hien inlet is subjected to this scenario to a greater degree than the northern inlet of Thuan An, where inlet conditions are more stable (Lam *et al*., 2007a). The leading cause of inlet morphological change at Tu Hien can be attributed to the longshore transport generated by obliquely incident breaking waves with more local effects from tidal flows, overwash, and cross-shore sediment exchange (Lam, 2002). Observation of the wind and wave patterns at the Tu Hien inlet suggest that the growth of the sand spit from the northern bank is directly related to longshore currents resulting from prevailing NE waves, as shown in Figure 7 (plate C). The newly formed sand spit at the inlet mouth changes the inlet channel direction towards that of the net littoral drift (Thanh *et al*., 2006). Overwash from normally incident waves with large runup height enhances the accretion of the sand spit developing on the northern side of the inlet (see Figure 8). The opening and closing of an inlet in a coastal lagoon can be conceptualized through five different stages, as presented in Figure 7.

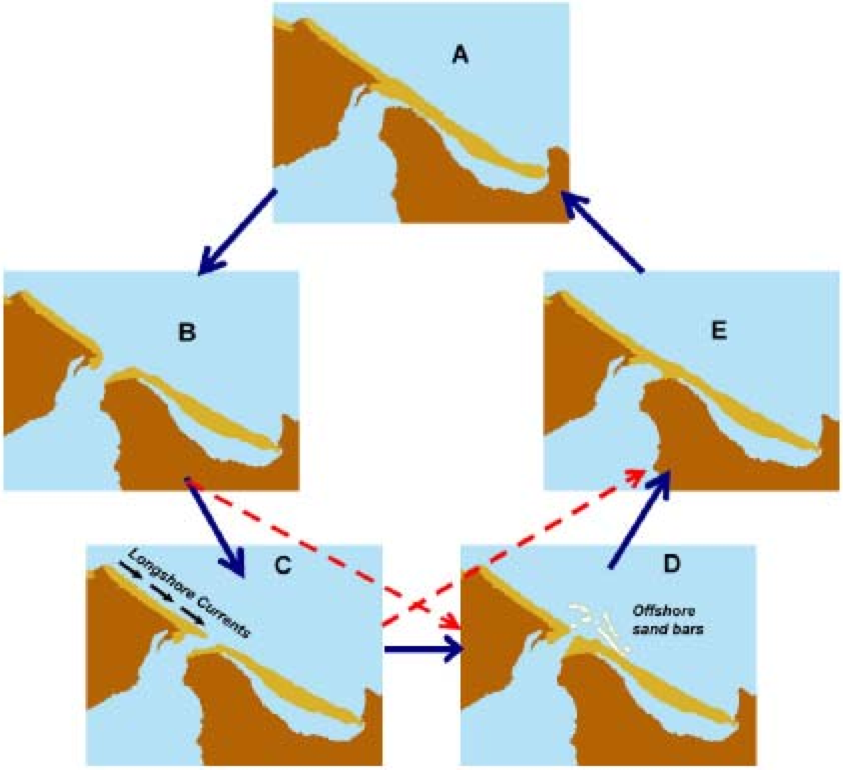


Figure 7 Schematization of inlet migration and closure (from Thanh *et al*., 2006)

a)

b)

Figure 8 Observation of wave action present along the coastline on the northern side of the Tu Hien inlet a) before and b) after overwash occurs

Semi-diurnal tidal fluctuations in combination with river discharge and wind setup (to a lesser degree) control the direction of water flow through the inlets. River discharge during the winter months may scour the bathymetry at the inlets. This process is observed at both inlet mouths, for example, Lam *et al.* (2007a) reported enlarging of the cross-sectional area at Thuan An inlet and Tu Hien inlet from 3,250 m^2 to 6,200 m^2 and 6,000 m^2 to 18,000 m^2, respectively. Net littoral drift towards the SE and the mouth of the Tu Hien inlet during the summer (Figure 7, plate C), in conjunction with deposited sediment associated with the tidal flow, cross-shore exchange, and river discharge through the inlet, creates a line of offshore sedimentation that ultimately forms an ebb shoal just outside of the inlet mouth (Figure 7, plate D). It is noted there is often an indirect relationship between longshore and cross-shore sediment transport and their impact on inlet closure. Low values of the longshore sediment transport results from waves being more normally incident, which in turn may imply that the cross-shore sediment transport becomes more dominant. In the reverse case, when longshore sediment transport prevails, the effects of cross-shore transport are often less important for inlet morphology change (Thanh *et al*., 2006).

Inspection of inlet morphologies over several years yields insights to patterns of evolution that help to explain the coastal processes involved in the inlet migration. Also, based on data compilation of inlet bathymetry, simulations of coastal processes may be carried out to increase the knowledge of the morphological behavior of inlets. Figures 9 - 12 show the change in inlet bathymetry between the years 2007 and 2009 for both the Thuan An and Tu Hien inlets. Inlet bathymetries were measured around the inlets during several field campaigns, including the February 2009 campaign. The bathymetrical changes in the Tu Hien inlet are more detailed due to the extra depth measurements taken during the field study in February 2009.

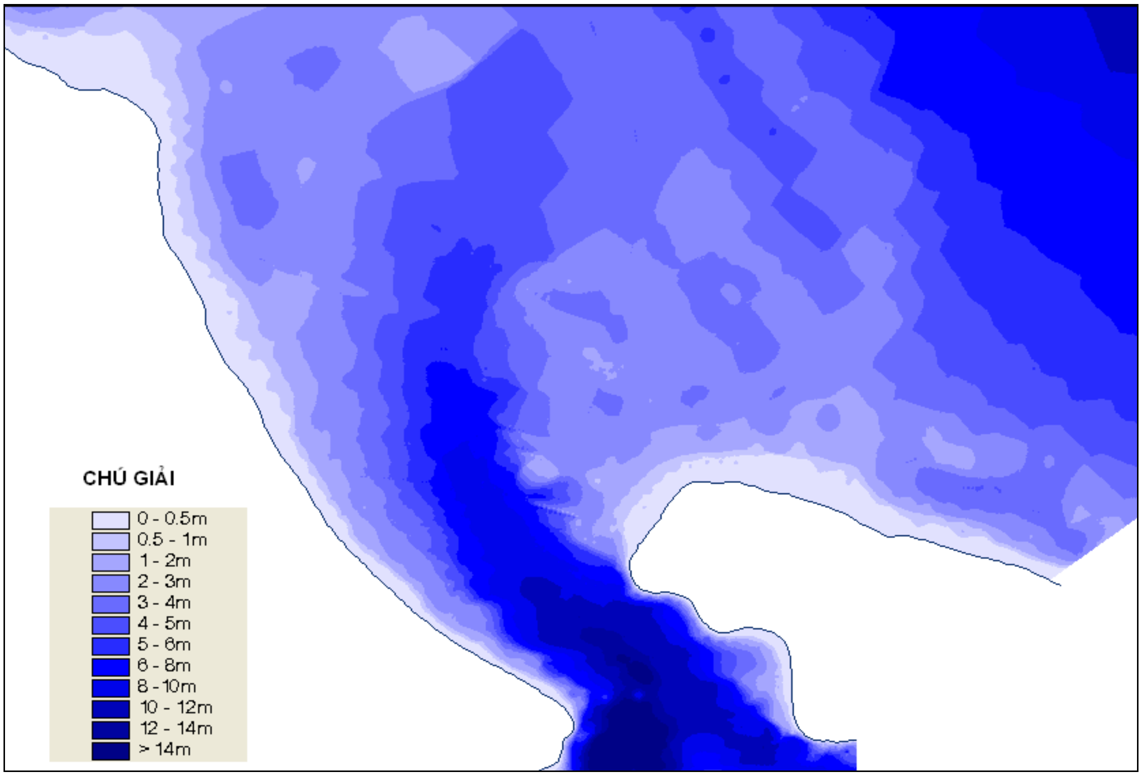


Figure 9 Bathymetry of Thuan An inlet area 2007 (after Nguyen, 2008)

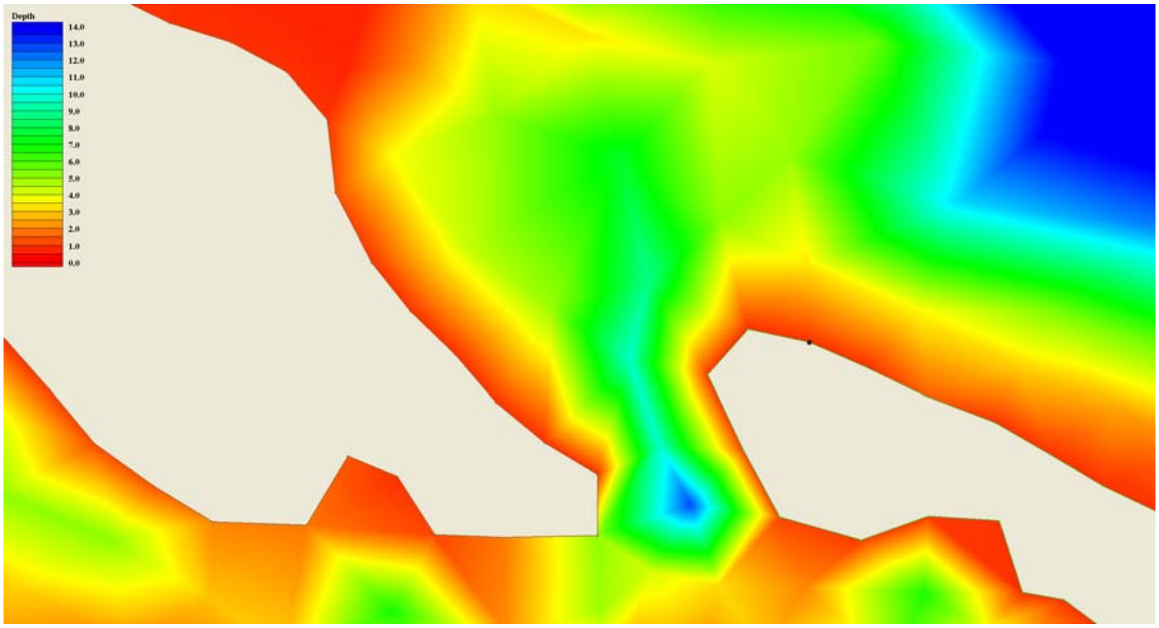


Figure 10 Bathymetry of Thuan An inlet area 2009 (depth given in meters)

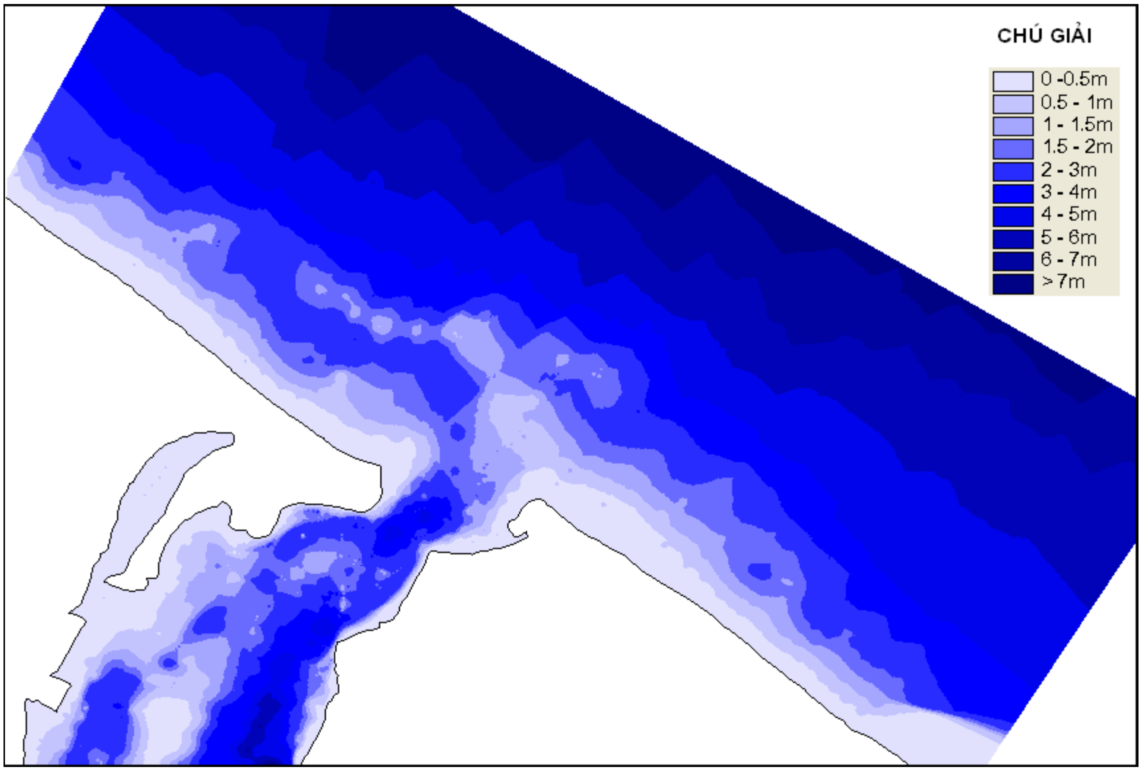


Figure 11 Bathymetry of Tu Hien inlet area 2007 (after Nguyen, 2008)

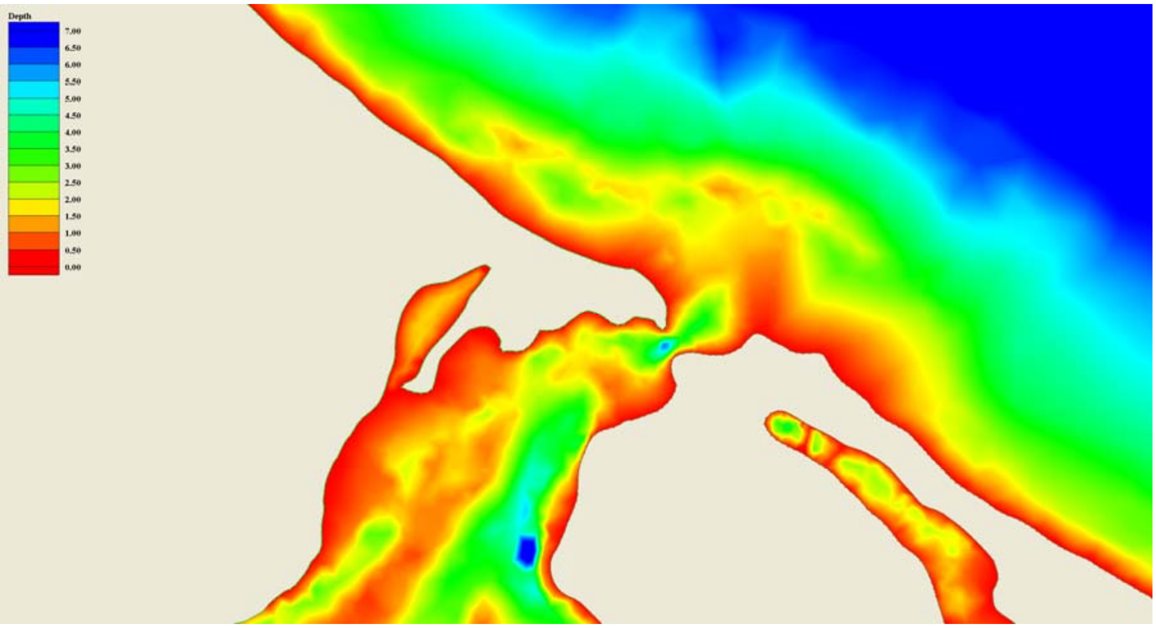


Figure 12 Bathymetry of Tu Hien inlet area 2009 (depth given in meters)

3.2.2 Quantification of Coastal Processes affecting Morphology

Inlet morphology changes are often intimately linked to the process of natural sediment bypassing, that is, the transport of sediment from the updrift side of the inlet to the downdrift side, assuming that longshore sediment transport is occurring. It is difficult to estimate the importance of the bypassing without knowledge of the longshore sediment transport rate at the inlet in relation to the lagoon discharge through the inlet. Bruun and Gerritsen (1959) proposed to use the ratio (r) between these two quantities in order to assess the relative importance of the sediment bypassing, employing the annual transport rate (M_{tot}) and discharge through the inlet during a tidal cycle (P; the tidal prism):

$$r = \frac{P}{M_{tot}} \qquad \text{Equation 1}$$

Values of r greater than the range of 200-300 strongly point towards predominant tidal flow by-passing with little or no shoal/bar formation, whereas values lower than the range of 10-20 indicate marked longshore sediment transport and the formation of shoals and bars through the process of sediment bypassing. A rough estimate of the average longshore current that drives the longshore sediment transport rate along the Tam Giang-Cau Hai lagoon system coastline varies between 0.3 – 1 m/s (Lam, 2002). This interval does not provide any conclusive evidence, using the above equation, for the importance of longshore sediment transport in the formation of the ebb shoal observed at the Tu Hien inlet. It can be expected that the magnitude of longshore sediment transport will produce r-values that are in the upper range, if the derived P-values from velocity measurements at the Tu Hien inlet under high river runoff or strong tidal flows is used. For example, measurements of the velocity at the center of the inlet mouth yielded a maximum velocity of approximately 1.9 m/s. Thus, relating the calculated discharge based on such measurements to the estimated average longshore sediment transport rates typically yields a value of *r* that is large, which promotes the idea of an inlet with morphology predominantly determine by tidal flow. However, because of the seasonal changes in inlet discharge conditions together with changing longshore sediment transport rates, the formation of the ebb shoal at the inlet mouth can most likely be associated with the effects of longshore sediment transport and sediment bypassing, where the process of reaching equilibrium for the shoal/bar-configuration may take several decades.

Waves overwash the coast and slowly accumulate sediment along the inlet mouth and on the ebb shoal as cross-shore deposited sediment. The incoming waves may carry sediment perpendicular to the coast, therefore reshaping the inlet mouth and creating a slight bend in the aggregated sand spit towards the lagoon. This process is divided among the seasons where coastal inlet erosion and ebb shoal sediment accumulation is present during the winter months and coastal accumulation and erosion from the offshore shoal/sandbar results from swell waves in the summer (Pattiaratchi and Ranasinghe, 2003). The variability in the shoreline location depending on seasonal and annual trends at Tu Hien and Thuan An inlets is displayed in Figure 13 and Figure 14, respectively, where measured shorelines are shown for the area around the inlets.

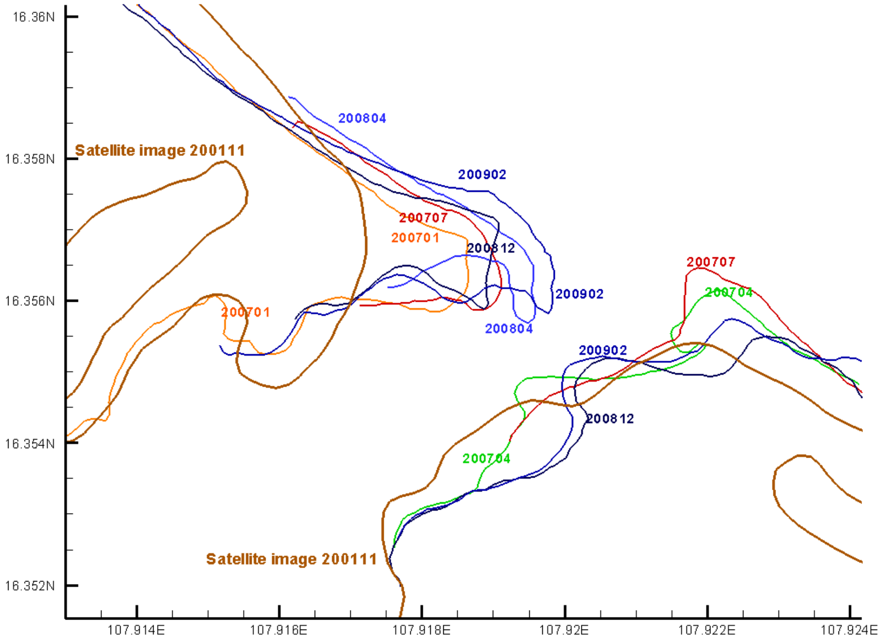


Figure 13 Measured shoreline position around Tu Hien inlet of Tam Giang-Cau Hai lagoon system

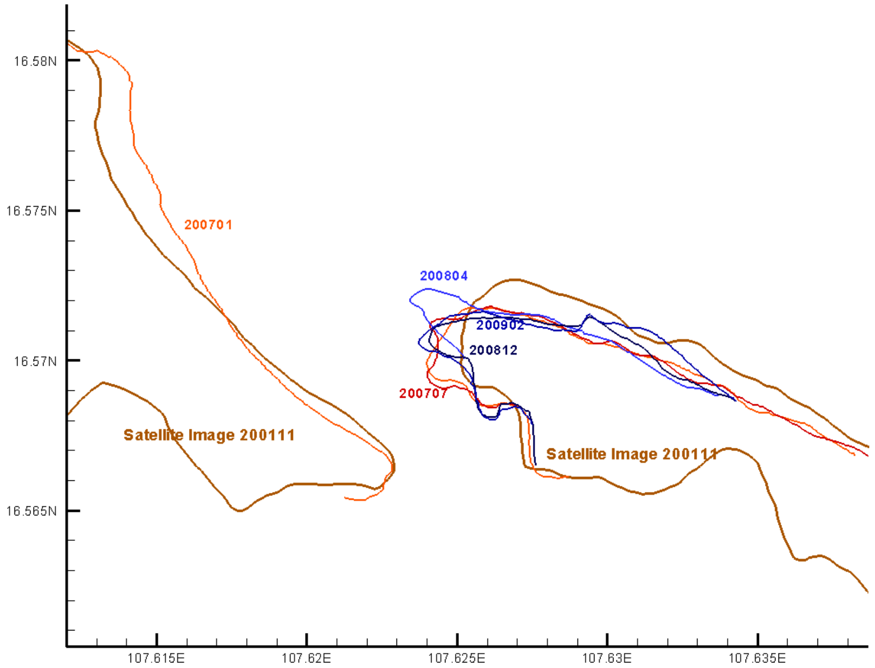


Figure 14 Measured shoreline position around the Thuan An inlet of Tam Giang-Cau Hai lagoon system

Longshore sediment transport is determined by the direction and magnitude of the waves. Large swell waves breaking along the coastline at acute angles produce large longshore sediment transport rates compared to small waves approaching at near-normal incidence. Variations in wave direction and magnitude due to storm events, changes in wind pattern, and differences in local shoreline orientation produces gradients in the longshore sediment transport that result in changes in the shoreline position. Observation and simulations with SMS indicate that inlet morphology is potentially dominated by the longshore sediment transport during the end of the winter monsoon season, when the inlet discharge is low and the waves will still be large. Figures 15 and 16 show the general scenario of sand spit accretion for the Thuan An and Tu Hien inlets, respectively. The development of the sand spits at both inlets is a function of the magnitude of longshore sediment transport as well as the amount of sediment available on either side of the inlet. Observation of the coastline to the south of Tu Hien inlet shows limited amount of sediment available for transport; therefore has the sand spit a larger potential to grow from the northern side. Measurements of the direction of the longshore current around the Tu Hien inlet indicates that the growth of the sand spit is in the direction of the prevailing net littoral drift (Lam, 2002).

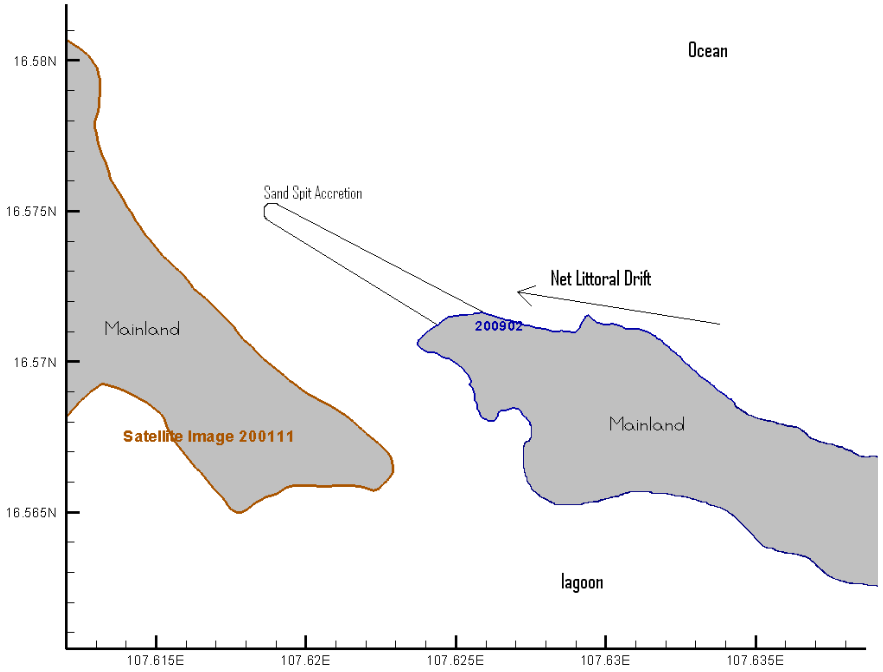


Figure 15 Direction of net littoral drift and the effect on spit growth at Thuan An inlet

*Image of Coastline for Thuan An on the northern bank (brown outline) is not updated with 2009 coastline data

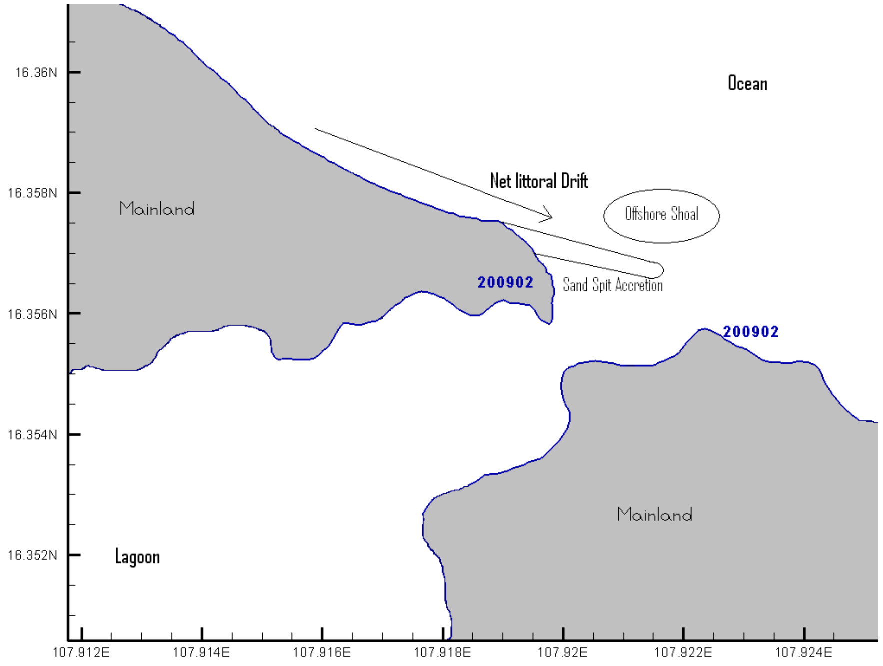
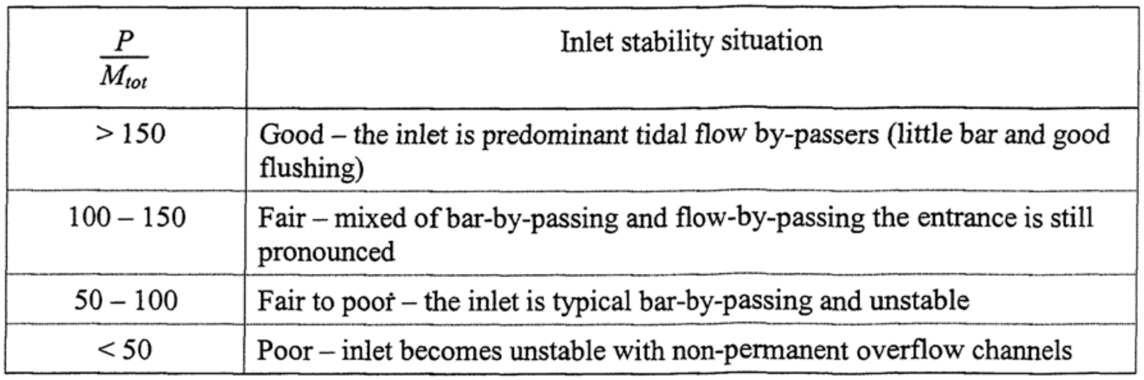


Figure 16 Direction of net littoral drift and the effect on spit growth at Tu Hien inlet

3.3 Impact of Inlet Migration and Closure

Inlet stability is directly related to the migration and closure of inlets and depends on tidal and wave conditions. Analysis of the tidal prism (P) and the total annual littoral drift (M_{tot}) at the Thuan An and Tu Hien inlets yield stability conditions ranging from fair to poor and poor, respectively, according to the criteria by Bruun and Gerritsen (1959) for inlet stability (see Equation 1). The assessments were made based on the criteria presented in Table 2, where P is measured in m^3/tidal cycle and M_{tot} in m^3/year. The numerical values for stability of both the Thuan An inlet and Tu Hien inlet were measured to be 10-60 and 10-20, respectively, according to Lam (2002; see also Lam *et al*., 2007a). The classification obtained based on Table 2 indicates that both inlets are not stable.

Table 2 Criteria for inlet stability proposed by Bruun and Gerritsen (1959) (from Lam, 2002)



$\frac{P}{M_{tot}}$	Inlet stability situation
> 150	Good – the inlet is predominant tidal flow by-passers (little bar and good flushing)
100 – 150	Fair – mixed of bar-by-passing and flow-by-passing the entrance is still pronounced
50 – 100	Fair to poor – the inlet is typical bar-by-passing and unstable
< 50	Poor – inlet becomes unstable with non-permanent overflow channels

Historical observations of the morphological evolution at Tu Hien inlet show a cyclic closure of the inlet mouth, a process which takes approximately four to five years (Lam *et al*., 2007a). The inlet closure at Tu Hien causes drastic changes in lagoon aquaculture and morphology. A new opening occurs approximately three kilometers south of Tu Hien at Loc Thuy resulting from a decreasing inlet cross-sectional area in conjunction with overwash from access river discharge (Lam *et al*., 2007a). This cyclic phenomenon was observed during the historic flood events of 1994-1999. Similar dramatic changes in the morphology occurred in the northern inlet at Thuan An during the historical storm event in November 1999. Intense precipitation from tropical cyclone EVE led to subsequent breaching of a more southern, naturally occurring inlet at Hoa Duan (Tuan, 2007). Inlet closure at Thuan An happens less frequently than at Tu Hien; the reason for this is most likely the larger river discharge into the Tam Giang lagoon near the Thuan An inlet that has a greater potential to scour the inlet during the winter months.

Efficient navigation between the lagoon and the open sea is of great significance for the communities bordering the lagoon. The disconnection of the lagoon from the sea has large impact on the local economy, which depends upon the fishery and aquaculture as well as the transportation of materials and supplies. The need to understand inlet migration and subsequent closure is intimately linked to knowledge of the hydrodynamics of coastal and marine processes, so that engineers can readily assess inlet stability and formulate strategies and measures to ensure that it is maintained.

Closure of inlets also changes the general balance between lagoon and oceanic conditions (that is, the fresh water and salt water influence), which may have large impact on the aquaculture and the lagoon ecosystem. Long periods of inlet closure lead to dramatic decreases in lagoon salinity due to the absence of normal quantities of ocean flow into the lagoon (Hung *et al.*, 2007). This greatly affects lagoon aquaculture, changing the desired conditions for growth of many aquatic habitats that ultimately lead to economic decline for the population surrounding the lagoon. Another important hydraulic aspect is also hampered during inlet closure. The water exchange between the lagoon and the sea, defining lagoon renewal time, is severely reduced. This has consequences for the water circulation inside the lagoon and the general mixing of the lagoon water.

4 Water Exchange in Coastal Lagoons

4.1 General Water Exchange

The water exchange between the Tam Giang-Cau Hai lagoon system and the sea is dependent on the morphological conditions prevailing at the inlets. Here, the Tu Hien inlet is studied more in depth due to the cyclic behavior of its opening and closure caused by greater instability, which has a significant effect on the water circulation within the lagoon system, especially the southern portion. The water exchange is affected by the tidal, wind, and river forcing present at these inlets together with the geometric and hydraulic properties (*e.g.*, roughness) of the inlets and the lagoon. At both inlets the tide is more or less diurnal, implying one high water and one low water per day. Different coastal processes determined by waves, currents, and sediment transport influence the inlet geometry and the water exchange through the inlet. A decreased water exchange is observed specifically at the Tu Hien inlet due to its degree of morphological change because of more unstable inlet conditions. As an illustration of the water exchange at Tu Hien inlet, Figures 17 through 22 display the simulated flow fields with the ADCIRC model under normal inlet conditions (denoted as Case 1 in Chapter 7, which discusses the results of the numerical model simulations) during approximately half a tidal cycle. Only the tide was employed to force the water exchange, which is typical for the dry season when river flow is negligible. The time step in the simulation was 2 sec.

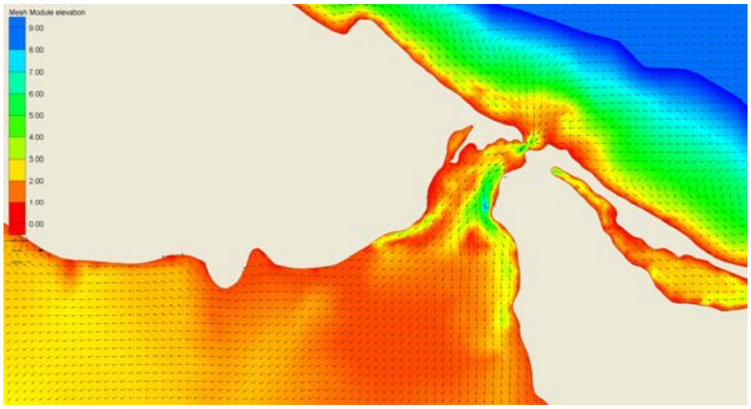


Figure 17 Simulated velocity field at Tu Hien inlet with the ADCIRC model together with depth contours (time step 50400)

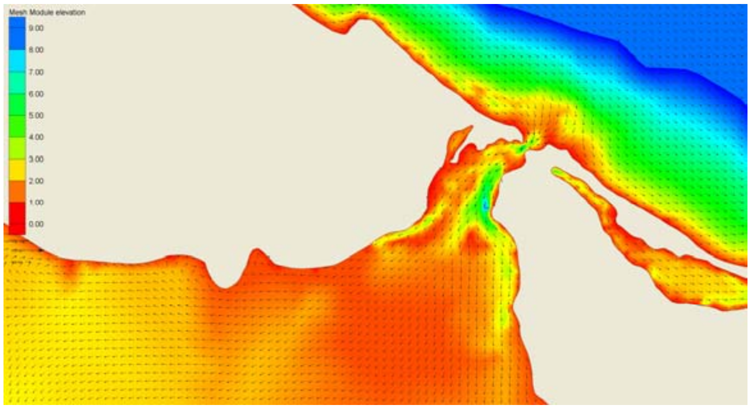


Figure 18 Simulated velocity field at Tu Hien inlet with the ADCIRC model together with depth contours (time step 54000)

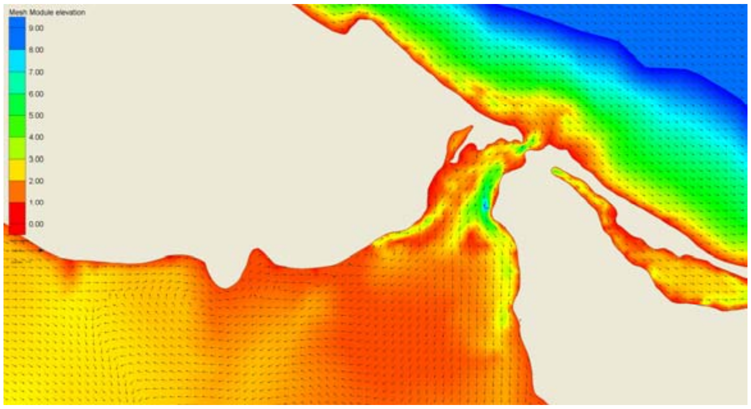


Figure 19 Simulated velocity field at Tu Hien inlet with the ADCIRC model together with depth contours (time step 57600)

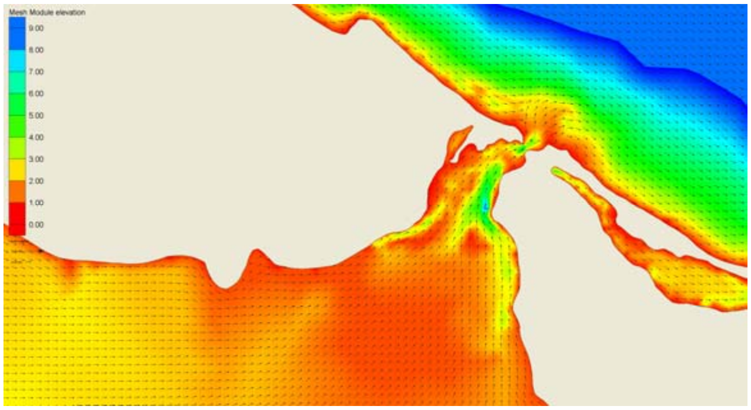


Figure 20 Simulated velocity field at Tu Hien inlet with the ADCIRC model together with depth contours (time step 61200)

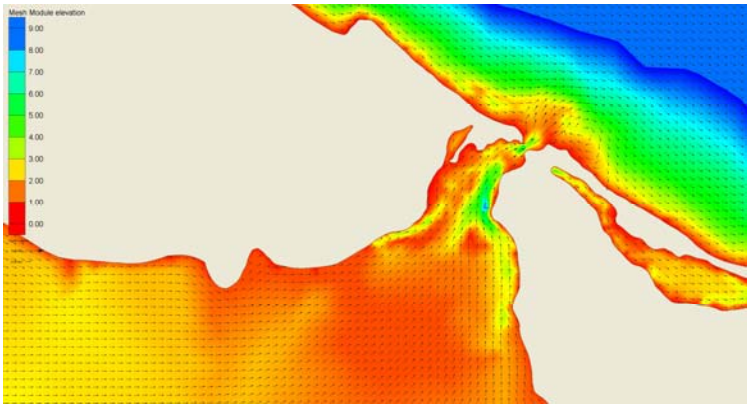


Figure 21 Simulated velocity field at Tu Hien inlet with the ADCIRC model together with depth contours (time step 64800)

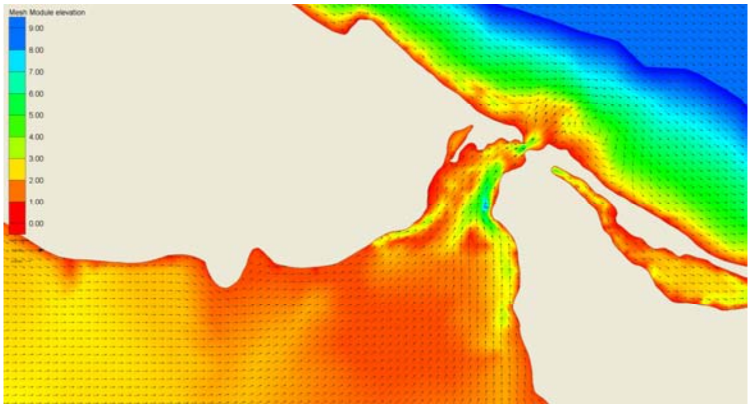


Figure 22 Simulated velocity field at Tu Hien inlet with the ADCIRC model together with depth contours (time step 68400)

4.2 Processes Affecting Water Exchange with the Sea

4.2.1 Tidal Variation and Waves

Currents and associated flow of water through the Thuan An and Tu Hien inlets are affected by variation in the tidal level. The water exchange resulting from the flow between the ocean and the lagoon increases as the tidal range increases. In general waves will have much less impact on the water exchange, although locally around the inlet some effects may be observed from surf-zone generated currents.

Typical wave conditions experienced at the Tam Giang-Cau Hai lagoon system are shown through the listing of wave parameters in Table 3. The wave parameters were modeled using SWAN at an offshore station just outside of the Tam Giang-Cau Hai lagoon system at location 17.00 degrees North and 108.00 degrees East over a nine-year time period from 01/01/1997 until 12/31/2006. All of the presented data are annual mean values as simulated from January 1 until December 31 during a particular year.

Table 3 Annual mean wave conditions modeled at an offshore station at 17° N and 108° E using SWAN

Year	H_{sig} (m)	T_{peak} (sec)	*Dir* (deg)
1997	1.8	6.8	109
1998	1.8	6.6	108
1999	2.1	7.5	106
2000	1.8	6.8	98
2001	1.7	6.6	105
2002	1.6	6.3	112
2003	1.8	6.7	103
2004	1.6	6.4	104
2005	1.8	6.6	107
2006	1.4	6.3	101

In the table, the value H_{sig} is the average significant wave height, T_{peak} the average peak spectral wave period, and *Dir* the average wave direction.

4.2.2 River Flows

As previously pointed out, major contributors to the water exchange between the lagoon and the sea are the rivers that discharge into the lagoon. During the rainy season, flow through the inlets may be dominated by the river discharge, and the inlet cross sections are too narrow to facilitate a smooth transfer of the water to the sea. Inlet widths that are too narrow create a choking effect on the water discharge, subsequently causing increased water levels in the lagoon and marked energy losses at the inlets because of large exit velocities. Thus, during the winter season, when large amounts of precipitation fall in a relatively short period of time, the effects of river discharges on the inlets seems to be fundamentally important for determining the effective exchange between the lagoon and sea. However, since there are limited direct measurements of the river flow available to quantify the effects of the rivers, it is difficult to assess how the rivers may benefit the water exchange within the Tam Giang-Cau Hai lagoon system. Such assessments have to fall back on different types of indirect measurements or mathematical modeling.

Coastal lagoons offer a possibility to estimate the water exchange based on the intruding salt from the sea using a mass balance approach. Tidal variations, especially during the summer months when the lagoon water depth and residual flow from the rivers are lower, cause the intrusion of salt through the seawater into the lagoon at rates controlled by different factors, including climatic and marine processes. The intruding seawater can often be distinguished from the fresh lagoon water because of the density difference, as depicted in the photograph (Figure 23) taken from the Tu Hien inlet during the field study carried out in the end of the February 2009.

The intrusion of sea water into the lagoon brings forth changes in lagoon water salinity and temperature, both which give rise to vertical and horizontal density gradients (Kjerfve and Magill, 1989). If moderate wind conditions are present at the lagoon and the tidal exchange is not too strong, vertical density gradients will be smaller than horizontal gradients, which create baroclinic currents that move against the main direction of flow along the bottom of the inlet. These currents help to cause further stratification and salinity gradients in the horizontal direction and to promote increased water exchange between the lagoon and the sea. A schematic of this process is given in Figure 24, where the densest water is forced downward vertically by gravity and subsequently redistributed horizontally due to water circulation from prevailing winds and inlet currents.

Figure 23 Saltwater intrusion at Tu Hien Inlet observed in February 2009 (front of the salt water penetrating from the ocean on the far side is indicated by the white line)

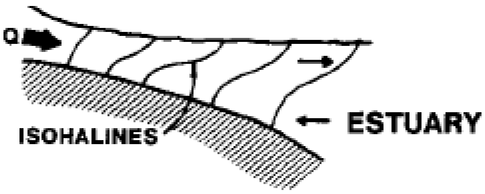


Figure 24 Schematic of stratification causing salinity gradients that may affect the water exchange at Tam Giang-Cau Hai Lagoon system (Jönsson 2008)

4.2.3 Wind

Winds may also modify the water exchange between the lagoon system and the sea, but the effect is probably much less than the tide and the river flow, because of the prevailing winds and the geometry of the lagoon. The magnitude and direction of the wind over the lagoon determines the wind-induced currents and water-level changes, which could set up gradients that force water to flow from the lagoon to the sea. A similar situation may arise where water flows towards the lagoon from the sea because the wind-induced currents and water levels produce gradients that induce inflow to the lagoon, in combination with the tidal variation. The wind effects on the water exchange vary over time as the wind changes direction and strength; however, over areas with small water depths their importance with respect to the water exchange becomes more evident (Jönsson, 2008). Figure 25 shows a schematic description of the wind effects in a small water body with limited horizontal depth: a wind setup is obtained in the direction of the wind and a slow water circulation is generated with a vertical structure.

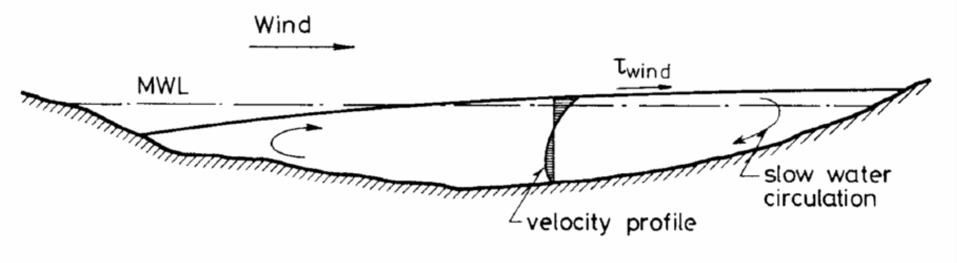


Figure 25 Effects of wind on water level and circulation in a small water body

The internal circulation in the lagoon is less complex compared to the exchange flow occurring between the lagoon and the sea. Mixing of water within the lagoon is dependent on variables that are easier to measure such as wind strength and lagoon water depth. These parameters directly affect the water circulation and mixing within the lagoon.

4.3 Effects of Marine Processes on Water Exchange

4.3.1 Longshore Sediment Transport

It is difficult to determine the rates of sediment transport due to the inability to accurately measure or model the governing parameters. Because of this gap in knowledge, the best estimates of sediment transport rates typically are within an error range covering one order of magnitude. For most coastal lagoon systems, longshore sediment transport rates play a large role in determining the water exchange between the lagoon and the sea, as transported sediments will deposit at the inlet mouths and reduce the exchange of water. The prevailing wave conditions, possibly with some influence from the wind, generate longshore currents that initiate and transport sediment towards the inlet that often accumulate around the inlet mouth; this is also the case at Thuan An and Tu Hien inlets (Tung, 2001).

Research over the past few decades has helped to solidify the theory on how longshore sediment transport interact with coastal inlets and what the effects may be with respect to water exchange. Sediment carried by prevailing longshore currents will be deposited in and around lagoon inlet mouths, creating a smaller width by the means of growing sand spits with consequences for navigation and water exchange (Pattiaratchi and Ranasinghe, 2003). The direction of the net annual longshore sediment transport and tidal variations govern the direction in which the sand spit will grow. Observations of both the Thuan An and Tu Hien inlets over time have shown that sand spit accretion at each inlet grows in the NW and SE direction along the coastline, respectively (Lam *et al.*, 2007a). The continued growth of these sand spits due to the prevailing longshore sediment transport will negatively influence the water exchange between the lagoon and the sea, and eventually the inlet may close completely preventing all exchange. At this moment the water in the lagoon becomes stagnant until a breach in the sand spit occurs allowing for renewed interaction between the sea and the lagoon.

4.3.2 Cross-Shore Sediment Transport

Cross-shore sediment transport includes the deposition and erosion of sediment in the direction perpendicular to the local shoreline orientation, and is the primary mechanism shaping the beach profile. Cross-shore process is of importance to study in the Hue region because of the frequent occurrence of tropical storms, which induce surge and large waves that tend to erode substantial amounts of sediment and transport it in the cross-shore direction (Tung, 2001). Large storms may also induce breaching of barrier islands and create new inlets, which is another result primarily of cross-shore processes. However, in comparison to longshore sediment transport near the inlets at Tam Giang-Cau Hai lagoon system, the transport and associated changes in bathymetry due to cross-shore processes should be less important for inlet migration and closure, although onshore transport and infilling may result from cross-shore transport during mild waves.

4.3.3 Lagoon Parameters and Renewal Time

In order to assess the effects of the water exchange on the Tam Giang-Cau Hai lagoon system it is important to quantify the capability of the lagoon to flush itself. This capability is often described through the renewal time of the lagoon, which depends on water exchange between the lagoon and the sea through the inlets, as well as general lagoon properties.

If the tidal flow is controlling the water exchange, a certain portion of the water in the lagoon will be exchanged at every cycle. In the case that “new” water in the lagoon is always involved in this exchange, the volume of the lagoon divided by the volume involved in the water exchange during each tidal cycle will give the number of cycles needed to replace the water in the lagoon. This number is one common measure of the capability of the lagoon to flush itself. However, the water that takes part in the exchange will not be entirely “new”, but some previously exchanged water will be included at any particular time, implying that the lagoon will never be completely exchanged. In order to quantify water exchange the term renewal time was defined as the time it takes before a certain portion of the lagoon water is exchanged or renewed. This portion is often selected to be 50% of the lagoon volume, and the corresponding renewal time is denoted by $t_{50\%}$. The renewal time is typically calculated under the assumption that complete mixing occurs within the lagoon at any given time. Thus, the renewal time may be determined by solving the following equation (Linnersund and Mårtensson, 2008).

$$\frac{dV}{dt} = -r_v V \qquad \text{Equation 2}$$

The volume of the lagoon is denoted by V and it is constantly changing with time as described by the term dV/dt. The variable r_v is the daily rate constant that is specific for each lagoon, but can be approximated by multiplying the ratio of the net inter-tidal volume to the total bay volume (k) by a factor of 2 (Linnersund and Mårtensson, 2008). The equation then becomes:

$$\frac{dV}{dt} = -2kV \qquad \text{Equation 3}$$

Manipulating Equation 3, and using the technique of variable separation, allows for integration of the equation using the proper initial conditions ($V = V_o$, when $t = t_o$) to yield the volume associated with a renewal time at $t_{50\%}$:

$$\int_{V_0}^{V_{50\%}} \frac{1}{V} dV = -\int_{t_0}^{t_{50\%}} 2k\,dt$$

Ultimately:

$$-\ln\left(\frac{V_{50\%}}{V_0}\right) = r_v\left(t_{50\%} - t_0\right)$$

Solving this for the renewal time $t_{50\%}$ with the conditions,

$$\frac{V_{50\%}}{V_0} = 0.5 \;\text{ and }\; t_0 = 0$$

yields Equation 4:

$$t_{50\%} = \frac{0.693}{r_v} = \frac{0.693}{2k} \qquad \text{Equation 4}$$

Applying Equation 4 for Case 1 (see Chapter 7) gives $t_{50\%}$ for normal conditions. Looking at Tam Giang and Cau Hai lagoons separately yields a net inter-tidal volume to lagoon volume of 0.17 and 0.033, respectively, per tidal cycle. Applying these k values in Equation 4 yields a $t_{50\%}$ of 2.0 days (49 hrs) and 10.4 days (249 hrs) for the the Tam Giang and Cau Hai lagoons, respectively.

5 Mathematical Modeling of Lagoon Flows

5.1 General

In order to further understand the processes controlling water exchange between Tam Giang-Cau Hai lagoon system and the sea, as well as the circulation in the lagoon system, a mathematical model was applied. Focus in the simulations was on conditions during the dry season when limited river discharge enters the lagoon and inlet migration and closure is more likely to occur. Thus, only tidal forcing was included in the simulation and the effects of river runoff was not modeled. Towards the end of the winter monsoon, the rainfall is less, but strong southerly directed alongshore sediment transport is still occurring, which causes spit development towards the south at Tu Hien inlet. The reduction of the inlet cross section, and possible inlet closure, seriously affects the water exchange and circulation in the lagoon resulting in strong negative impact on the lagoon water quality. Since the Tu Hien inlet is most sensitive to inlet migration and closure, different scenarios with regard to the influence of a reduced inlet cross-sectional area was investigated for this inlet.

Calculations of lagoon flows with respect to measured bathymetry, lagoon geometry, and oceanic hydrodynamic conditions were accomplished using a powerful hydrodynamic simulation program located within the SMS 10.0 (Surface-water Modeling System). This program utilizes regional offshore ocean data (*e.g.*, tidal forcing) in order to simulate coastal and nearshore circulation, including the effects of the ocean flow directly on a lagoon. The program used, ADCIRC, may be employed to solve time-dependent, free-surface water circulation and transport problems in two and three dimensions, and it was utilized for its flexible calculation of tidal circulation through application of a structured, finite element grid (Adcirc.org, 2009). In the following a brief summary of the ADCIRC model is provided together with the implementation in the present study. Chapter 7 presents the results of the model application to the Tam Giang-Cau Hai lagoon system.

5.2 Application of ADCIRC

5.2.1 The ADCIRC Mesh and Inputs

Before simulations can be carried out with the ADCIRC program, a detailed grid must be matched on top of the coastline data for the area of interest, in this case the Tam Giang-Cau Hai lagoon system in central Vietnam. First the depth and coastline files are loaded and converted to similar units of UTM before the meshing grid is created. The coastline files originated from a combination of Google Earth satellite images and measured inlet changes in February 2009, using the Garmin GPS coordinate measuring device (Google Earth, 2009). Bathymetric data relating to the Tam Giang-Cau Hai lagoon system were provided by the Institute of Mechanics in Hanoi. These data included previously recorded depths together with depths measured at Tu Hien inlet during the February 2009 field study. The bathymetric contours can be seen in Figures 26 and 27 for the Thuan An and Tu Hien inlets, respectively, and for the entire lagoon system in Figure 28.

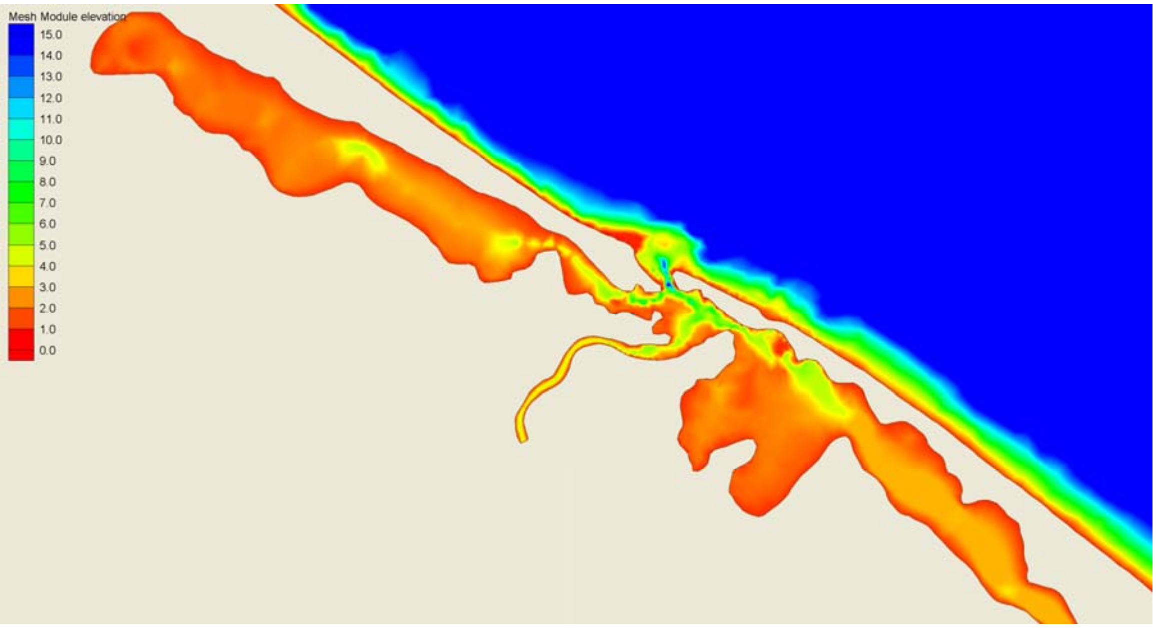


Figure 26 Bathymetric contours around Thuan An inlet and in Tam Giang lagoon

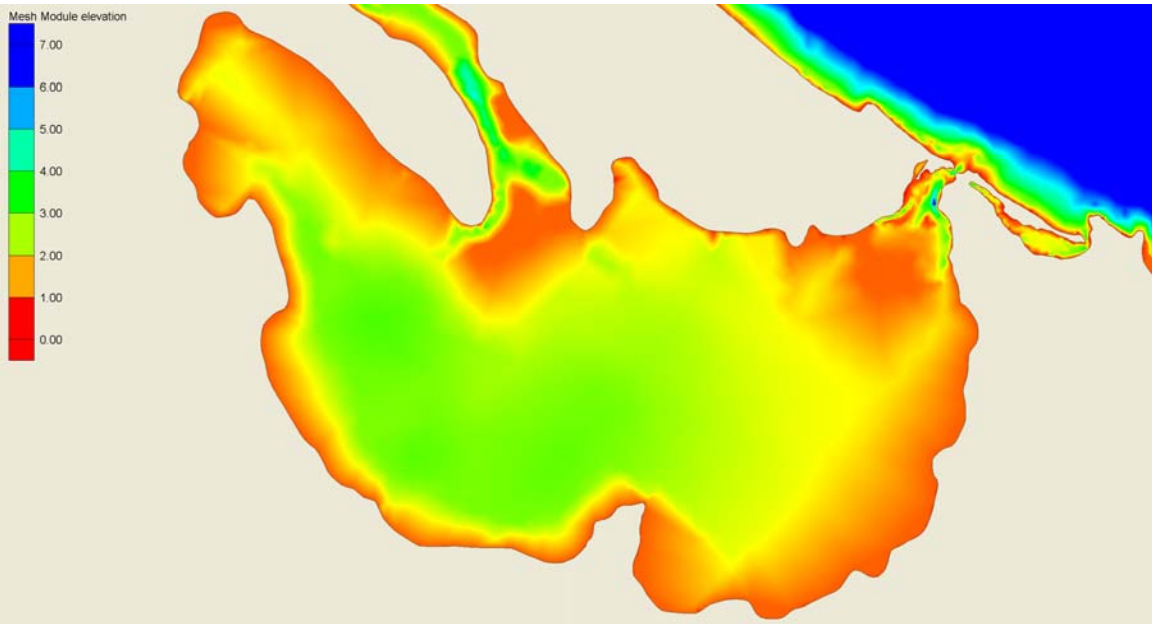


Figure 27 Bathymetric contours around Tu Hien inlet and in Cau Hai lagoon

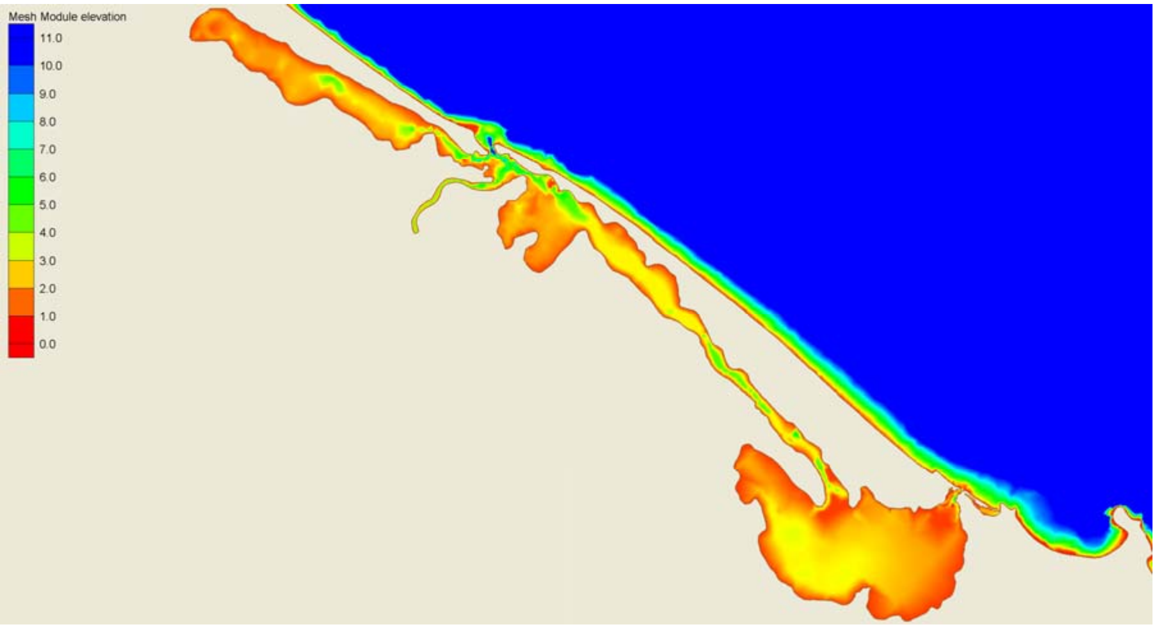


Figure 28 Bathymetric contours in the Tam Giang-Cau Hai lagoon system

Because ADCIRC is a regional model and the modeling area normally is substantially larger than the lagoon itself, the size of the mesh triangles must be decreased and highly concentrated in and around the lagoon in order to obtain an acceptable resolution in the area of interest. SMS and ADCIRC are highly powerful tools in this respect since it is relatively easy to employ an algorithm to refine the mesh near the lagoon while still leaving the ocean mesh unrefined, thus saving computational time. The employment of the finite element mesh is used to solve the complex partial differential equations by approximating functions, therefore decreasing their complexity over the domain (Linnersund and Mårtensson, 2008).

Before the mesh can be generated, the user must specify in ADCIRC which part of the model domain is land and which is water, in order to implement the meshing only within areas of water. If this is not done properly, the meshing will be allocated to areas of land and ADCIRC will try to force wave conditions in spots where land exists. In order to correctly modify the size of the mesh with regard to its location to the lagoon, an algorithm labeled *FinalSize* was created and implemented into ADCIRC through the Data Calculator tool. Once this function was created, a final refined equation was added through an application called the smooth function. This equation in SMS allows the elements to grow faster as the distance away from the center point increases; however it increases the amount of elements near the center point. The value of the smooth function was set to have a constant value of growth at 0.5. The final ADCIRC meshes are shown in Figures 29 and 30, where inlet locations in Figure 30 are denoted by the red circles. The derivation of the *FinalSize* algorithm encompassed the development of a series of equations:

$$DisTance = \sqrt{\left(x - x_{cp}\right)^2 + \left(y - y_{cp}\right)^2}$$

$$Scale = \sqrt{\frac{DisTance}{MaxDisTance}}$$

$$FinalSize = Max\left(25, \left(40scale * wavelength\right)\right)$$ Equation 5

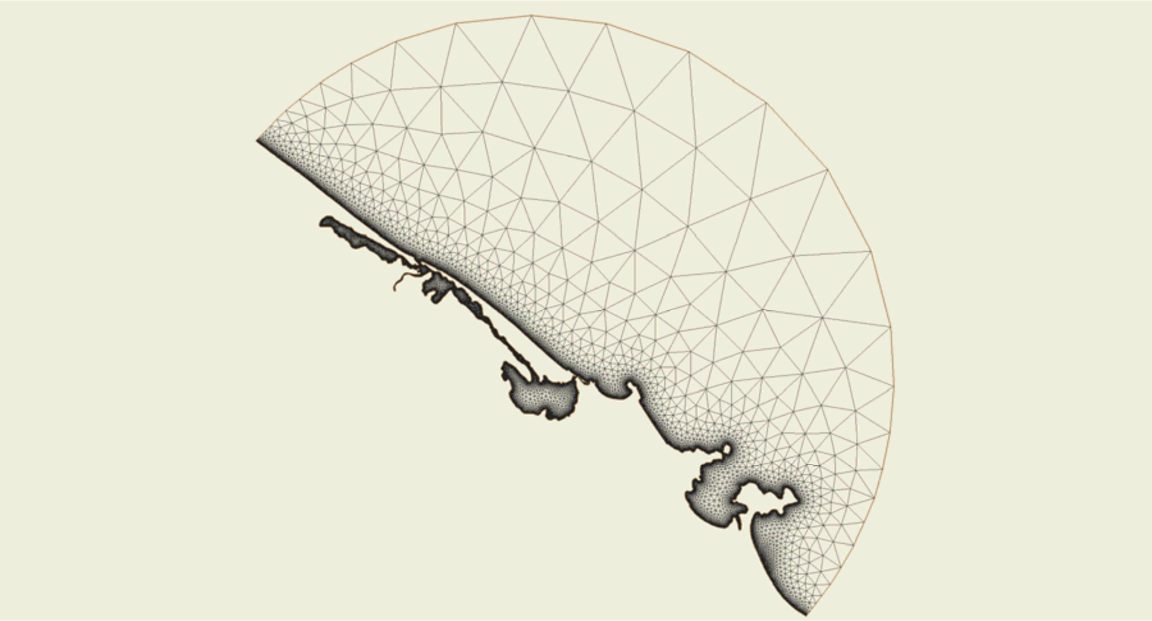


Figure 29 ADCIRC mesh of Tam Giang-Cau Hai lagoon system and surrounding domain

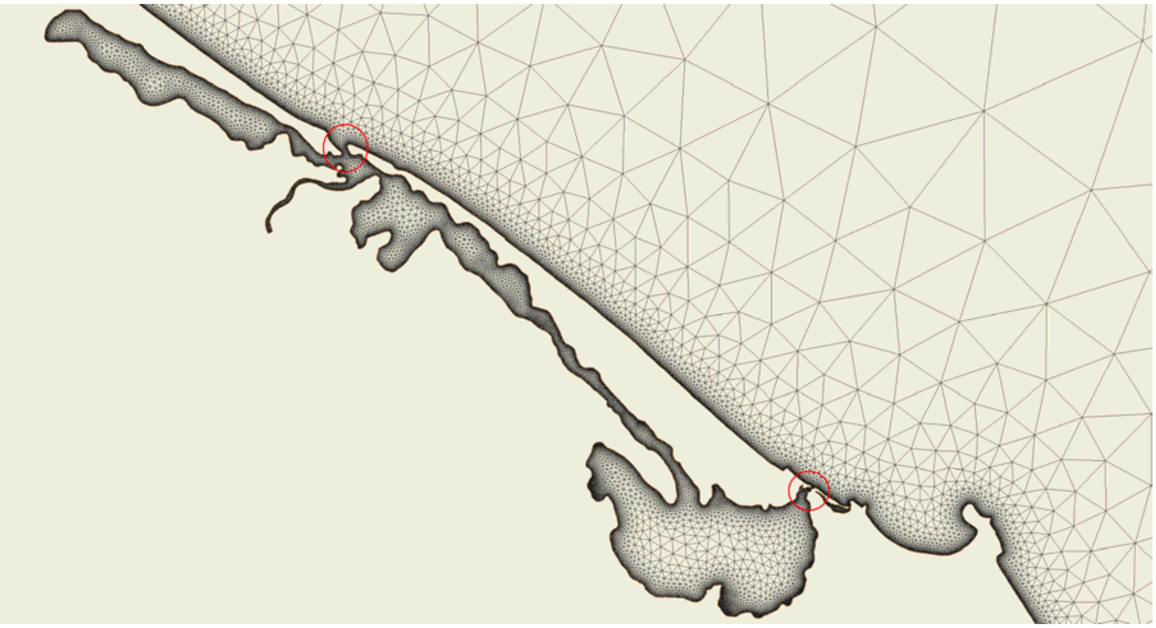


Figure 30 ADCIRC mesh of Tam Giang-Cau Hai lagoon system with inlets circled

The density algorithm for the ADCIRC meshing was employed with emphasis on the Tu Hien inlet to the south, creating a meshing grid that was finest in this region. An additional refinement point at the Thuan An inlet in the north was not added due to its more stable conditions, larger size, and less importance with regard to water exchange and local lagoon conditions compared to Tu Hien inlet. The average conditions for shallow waves were chosen at 20 second intervals following the SMS tutorial (SMS Surface Water Modeling System Tutorials, Version 8.1), with its center located at x = 811982.074, y = 1810509.886 within the Tu Hien inlet mouth. Distances were calculated using the UTM coordinate system. The *DisTance* function determines the scalar distance each scatter point is from the mesh point center, which is denoted by x_{cp} and y_{cp} for the two coordinate directions. The location of each scatter point is recorded as x and y.

Since a refinement center was chosen at the Tu Hien inlet another function, *Scale*, is needed before the *FinalSize* function can be applied to the ADCIRC model. The purpose of the *Scale* function is to assign numerical numbers ranging from 0-1 for each node on element center, where 0 pertains to the refinement center at the Tu Hien inlet and 1 represents the farthest most elements. Through this procedure, ADCIRC creates a radial mesh that is generated outwardly from the refinement center, where each the size of element will increase rapidly as the elements are generated further from the center (SMS, 2003). The maximum distance used in the refinement formula is 155568 meters for the generated ADCIRC mesh.

The *FinalSize* function utilizes the *Scale* function to determine the actual size of each generated element. The parameter Q denotes the minimum allowable element size for the created mesh and was chosen to be 20 meters in order to create sufficient resolution to investigate the flow within the lagoon. The maximum allowable element size was set to be 10,000 meters, which occurs for elements that lie within the sea at the farthest radial distances from the refinement point. The remaining part of the equation determines how rapidly the elements will grow to reach their maximum element size, utilizing the *Scale* function by multiplying it with the previously calculated *Size* function (SMS, 2003).

5.2.2 Triangulation of Elements

The generated ADCIRC mesh may have errors that need to be fixed directly by the user in order to ensure the validity of the solution of the momentum and continuity equations. Each element node was assigned a maximum value of connecting line segments, 7, in order to both decrease the computational time and increase the accuracy of the solution. Readjustments of nodal positions in conjunction with the addition of new nodes and elements are applied in order to ensure that each element is not either two times greater than or less than one half the size of all adjacent elements (Linnersund and Mårtensson, 2008).

The generated mesh is comprised of small, individually unique, finite triangles that differ in size, length, area, and position. Each triangle contains specific data with relation to such components as bathymetry, water depth, area, and volume. For each finite triangle, ADCIRC employs a counter-clockwise system of notation, labeling each node that the element consists of. Figure 31 shows an example of what a finite element looks like after the mesh is generated in ADCIRC.

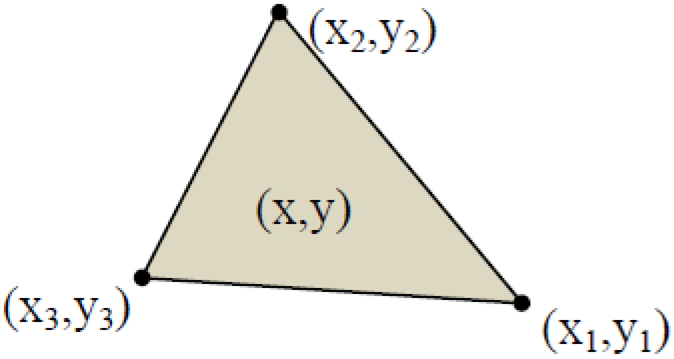


Figure 31 Depiction of generated element and respective nodes in ADCIRC (after Linnersund and Mårtensson, 2008)

5.2.3 ADCIRC Governing Equations

In order to obtain an accurate solution of the governing equations in the ADCIRC model the calculated time step was set to 2 sec. If a too large time step is selected it will produce a solution that is not accurate and large discrepancies may be obtained compared to the observed water surface elevations (WSE). For more detailed discussion of time step selection, see section 5.1.4 of Linnersund and Mårtensson (2008).

In the simulations, a certain spin-up time is needed to avoid shock-loading of the model when the forcing is employed. Thus, the model simulation time was extended beyond the time period of interest, which normally encompassed about one week, leaving room for one full day of spin-up time in order to proceed to full forcing conditions. General model output concerning both WSE and velocity were recorded every 60 minutes under tidal forcing frequency constituents relating to *LeProvost* tidal input data (Le Provost *et al.*, 1994) provided by the Institute of Mechanics in Hanoi, Vietnam.

ADCIRC uses the full set of mathematical expressions to perform calculations for both the momentum and continuity equations in two and three dimensions. The program solves the momentum equations in combination with the Generalized Wave-Continuity Equation (GWCE) (Luettich and Westerink, 2004).

Momentum

The depth-averaged velocities are calculated in 2-D through the vertical integration of the momentum equations, yielding the following equations (Luettich and Westerink, 2004):

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}-fV=-g\frac{\partial\left(\zeta+P_s/g\rho_o-\alpha\eta\right)}{\partial x}+\frac{\tau_{sx}}{H\rho_o}-\frac{\tau_{bx}}{H\rho_o}+\frac{M_x}{H}-\frac{D_x}{H}-\frac{B_x}{H}$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+fV=-g\frac{\partial\left(\zeta+P_s/g\rho_o-\alpha\eta\right)}{\partial y}+\frac{\tau_{sy}}{H\rho_o}-\frac{\tau_{by}}{H\rho_o}+\frac{M_y}{H}-\frac{D_y}{H}-\frac{B_y}{H}$$

Equation 6

The variables in the momentum equations are defined as:

Q_x, Q_y = Flux per unit width in *x* and *y* direction
D_x, D_y = Moment dispersion in *x* and *y* direction
M_x, M_y = Vertically integrated lateral stress gradient in *x* and *y* direction
B_x, B_y = Vertically integrated baroclinic pressure gradient in *x* and *y* direction
τ_{sx}, τ_{sy} = Imposed surface stresses
τ_{by}, τ_{by} = Bottom stress components
ρ_0 = Reference density of water
P_s = Atmospheric pressure at the sea surface
H = Vertically integrated lateral stress
η = Newtonian equilibrium tide potential
f = Coriolis parameter

Continuity

The GWCE is used in conjunction with the momentum equations in order to calculate the WSE using the vertically integrated continuity equation, which is expressed as (Luettich and Westerink, 2004):

$$\frac{\partial H}{\partial t}+\frac{\partial}{\partial x}\left(UH\right)+\frac{\partial}{\partial y}\left(VH\right)=0$$

Equation 7

U, V = depth-averaged velocities in the in *x* and *y* direction
H = total water column thickness
t = time
h = bathymetric depth (distance from the geoid to the bottom)
ζ = free surface departure from the geoid

5.2.4 Model Inputs and Parameters

The ADCIRC regional model requires the user to set certain model parameters in order to create more precise simulation results over specific areas. The final meshing grid imposed over the model area can be seen in figures 29 and 30. Element size was chosen to be minimally 20 meters large, which is a small enough value to allow for a higher amount of inlet simulation accuracy at the expense of modeling run time. The balance between run time and simulation accuracy was chosen to favor accuracy in order to better compare the simulation results at the inlets with measured data from the field campaign. The total number of elements and nodes created for the finalized grid were 108,964.

The allocated values for the model parameters followed recommendations in the SMS manual directly. Bed friction determines the magnitude of the velocity and the friction coefficient is often the main calibration parameter when comparing model simulation results with data. In the present simulations, the value for the bed friction coefficient was initially set to 0.0025 following the SMS manual, and this value was subsequently confirmed as a representative value by comparison with data obtained during the field campaign.

As previously mentioned, the time step was specified at 2 sec to produce numerically accurate simulation results, although execution times became rather long for the employed grid. Overly large time steps produce inaccurate simulation results (Linnersund and Mårtensson, 2008), therefore as a precautionary measure the time step suggested by the model tutorial was halved in order to increase accuracy of results. Conditions applied to the offshore boundaries of the model were specified following LeProvost regional tidal data input, and these input values were provided directly by the Institute of Mechanics in Hanoi. The final parameter values controlling the model execution used in all subsequent simulations with the ADCIRC model are listed in Table 4. The selected simulation time was a compromise between including a sufficient number of tidal cycles to provide information on the water exchange and lagoon system circulation and to obtain acceptable model execution times.

Table 4 Final computational control parameters

Model Parameter	*Selected Value*
Time step	2 seconds
Simulation time	8 days
Output	60 minutes
Ramp Function	1 day

Simulated values were recorded every 60 minutes as indicated by the output time in Table 4. Also, there was a period in the beginning of each simulation that allowed for a gradual increase of the forcing to its full value (spin-up time), which was chosen to be 1 full day, as represented by a Ramp Function (SMS, 2003).

6 Field Measurements

6.1 Data Collection

The field campaign and collection of data began at 5:30pm on February 22, 2009 at field stations S01 (16° 21.747'N and 107° 55.192'E) and S02 (16° 21.027’ N and 107° 54.910’E) approximately 200m outside and 200m inside of the lagoon, respectively. Data were collected for almost two days using three different instruments. A description of each of these instruments, the purpose of their application, and locations where they were placed are described in the following.

The DNC-2M instrument (Figure 31) is of cylindrical shape with a propeller at one end, and it used to measure current speed at a given depth over a specific period of time. One of these instruments was placed at each field station, S01 and S02, recording the observed sea and lagoon current, respectively, from 5:30pm February 22 until 6:00am February 24 (local times). Measurements were obtained at 15 minute intervals, and in total 36 hours and 45 minutes worth of useful data were collected to be employed for comparison with the ADCIRC model simulations. The instruments were placed at 2.5m depth from the water surface at each location and the average water depth was approximately 4.8m at both locations. Because it is known that horizontal velocities differ with distance from the bed, approximately following a logarithmic increase, the present depth was chosen in order to obtain a value corresponding to the depth-averaged horizontal velocity.

Figure 31 Picture of DNC-2M current measuring instruments utilized at field stations S01 and S02

The OBS-3A instrument (Figure 32) is a thin, cylindrical tube used to measure wave height, wave period, depth, and WSE. The time interval between recordings was set at 15 min, matching that of the DNC-2M device. Inspection of the measurement time series yielded 36 hours and 45 minutes worth of valid data to be used for modeling. The device was deployed during the same time period as the DNC-2M, however only at field station S01 due to the lack of an additional instrument. Thus, the WSE could not be recorded inside the lagoon at field station S02, but only the measured WSE at field station S01 was available to validate model simulations. The measured WSE and velocity is presented in section 6.2.

Figure 32 Picture of OBS-3A WSE measuring instrument utilized at field station S01

Measurements of the coastline (February 2009) were done using the Garmin GPS system (Figure 33). The Garmin GPS system is a small, handheld global positioning system that utilizes remote connection to several satellites in order to locate and record the position. The measurement accuracy was estimated to be within 3m, as noted by the device itself. Measurements of shoreline position at the Tu Hien inlet, both along the north and the south banks, as well as along the south bank of the Thuan An inlet were recorded every 10 seconds as the user walked along the shoreline. Due to time restrictions, the northern bank of the Thuan An inlet could not be measured, and in the modeling, data were employed with respect to bank conditions from the 2006. In reality the north bank will also have experienced morphological change; however, the effect of this change around Thuan An inlet with regard to the water exchange between the lagoon and sea is small compared to corresponding effects at Tu Hien inlet. All instruments utilized during the field campaign were provided by the Institute of Mechanics in Hanoi.

Figure 33 A Garmin GPS device used for shoreline surveying in Hue, Vietnam (depicted model is a Garmin GPS 76 Handheld; see http://www.triginstruments.co.nz)

After setting up the DNC-2M and OBS-3A instruments at the measurement stations, depth soundings were carried out around the Tu Hien inlet. The process of collecting the inlet depth data involved another Garmin GPS device, used to locate the position of the recorded depth data, in combination with a ultrasonic sensor that recorded water depths. The depth sensor was mounted to the side of a small boat and synchronized with the Garmin GPS system so that every 10 seconds both the depth and the position would be recorded simultaneously. Again, the precision in the recorded location for the depth measurements was calculated by the Garmin GPS to be within 3 meters of the actual position. Depth measurements were recorded for the Tu Hien inlet as well as for adjacent points outside the inlet mouth. The measurements were added to the existing bathymetry data for the lagoon, and a combination of measured and interpolated depths was subsequently used in the ADCIRC model simulations.

6.2 Data Obtained

During the field campaign at the inlets in February 2009, data regarding water surface elevation and velocity were recorded in total for approximately a 36-hour period. The data were obtained from two points, one approximately 200m outside of the lagoon mouth at field station S01 and the other approximately 200m into the mouth of the lagoon at field station S02, as shown in Figure 34. The measured data within the lagoon at station S02 were used as a basis for validation of the simulated velocities obtained from ADCIRC. Figure 35 displays the measured velocity magnitude and WSE for field station S01 (outside the lagoon), whereas Figure 36 shows only the measured values of velocity magnitude for station S02 (inside the lagoon), since there was no instrument measuring the change in WSE at the latter location during the field campaign.

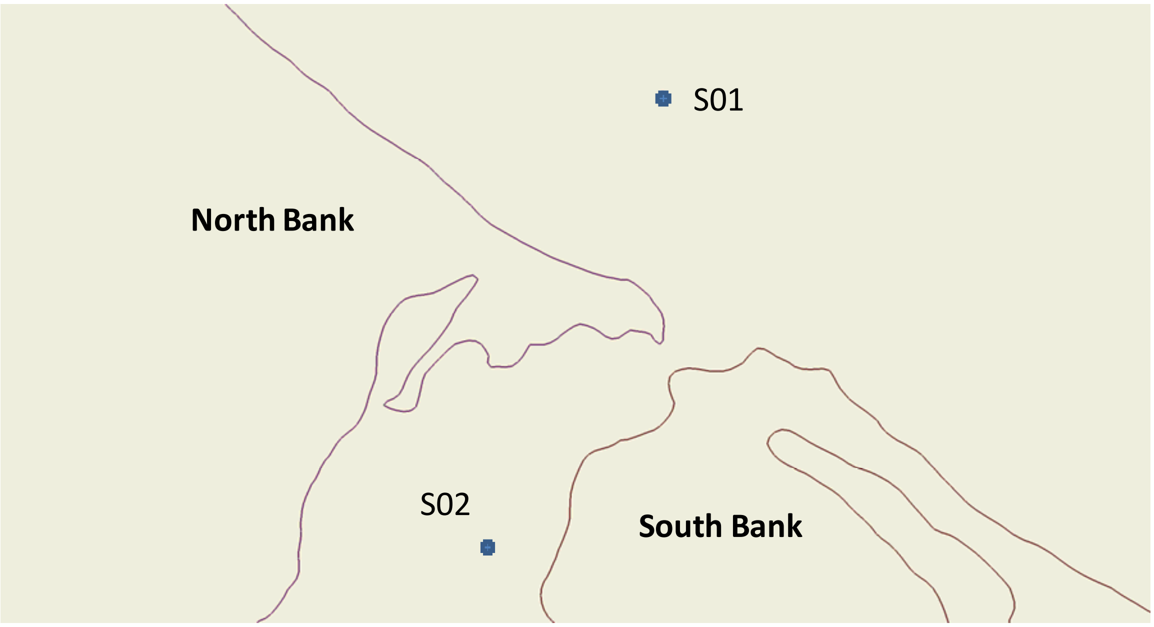


Figure 34 Map of field measurement station S01 and S0 at Tu Hien inlet (the coordinates of S01 and S02 are 16° 21.747'N, 107° 55.192'E and 16° 21.027’ N, 107° 54.910’E respectively)

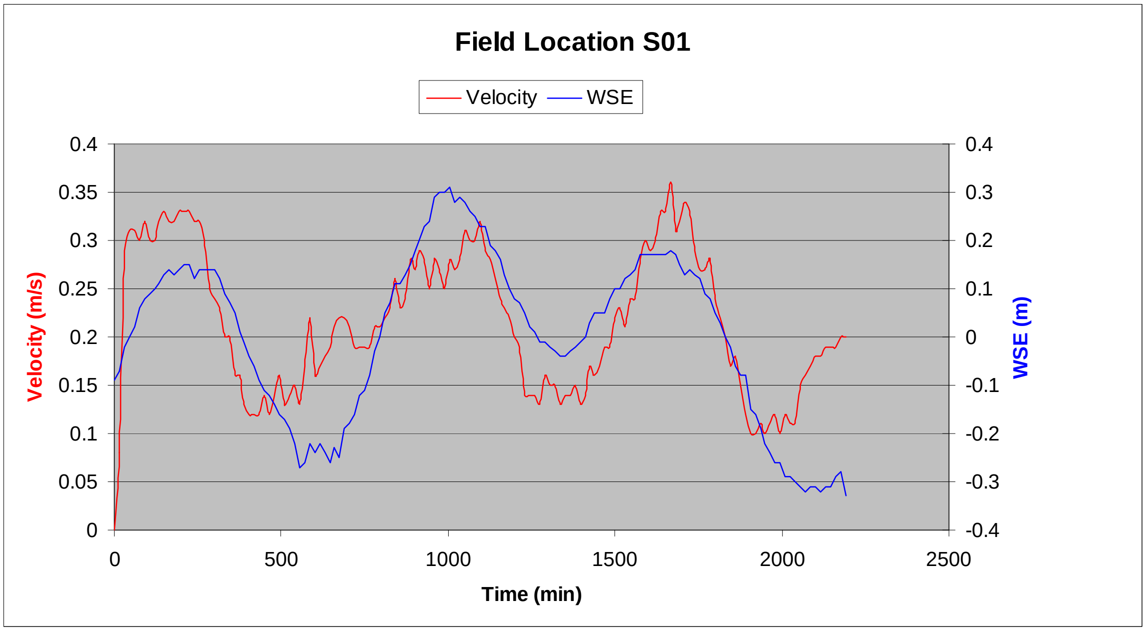


Figure 35 Measured velocity magnitude and WSE at station S01 (about 200m outside the Tu Hien inlet)

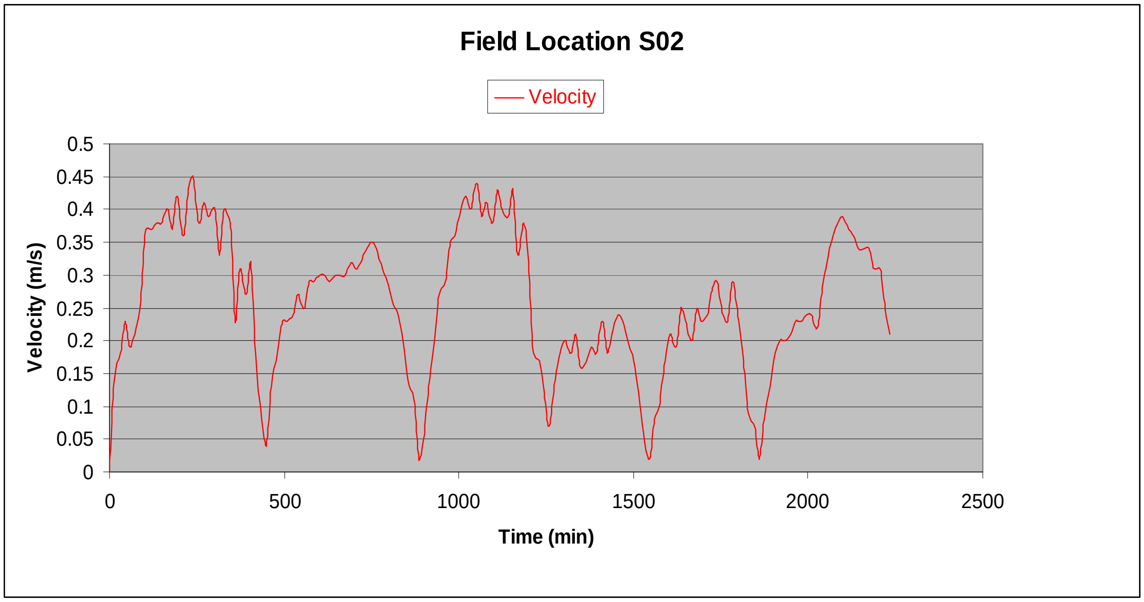


Figure 36 Measured velocity magnitude at station S02 (200m inside the Tu Hien inlet)

7 Modeling Results

The model results in the following section were obtained using the meshed grid created for ADCIRC within SMS, as presented in Figures 29 and 30. Model validation was carried out by comparing the measured and simulated velocity at station S02 shoreward of the inlet under tidal forcing at the boundary administered through the LeProvost global tidal data. A general sensitivity analysis was performed for certain parameters and model performance was evaluated with respect to the best fit simulated versus measured velocity, discussed in more detail in section 7.2.

In order to investigate the effects of inlet migration and closure on the water exchange between the lagoon system and the sea, inlet geometry was modified to represent different possible flow scenarios (see section 7.3). As previously pointed out, these scenarios focus on modifications at Tu Hien inlet, since this inlet has been observed to experience stronger morphological change due to waves and currents than the northern inlet at Thuan An. The presented scenarios include simulations of water exchange with the Tu Hien inlet completely closed and partially closed from sand spit development. The results from these scenarios were compared against simulations for normal conditions, where no modifications were made to the inlet geometry as observed in February 2009. Table 5 presents a summary of each scenario simulated.

Table 5 Summary of water exchange scenarios

Case	Model	Inlet Conditions	Model Forcing
1	ADCIRC	Both Open (normal)	Tidal
2	ADCIRC	Tu Hien Partially Closed	Tidal
3	ADCIRC	Tu Hien Completely Closed	Tidal

As discussed earlier, the focus of the simulations was on water exchange due to tidal forcing only, since the most critical conditions regarding inlet migration and closure occur towards the end of the winter monsoon when the river flow is small. However, in the general case, prevailing winds, large-scale coastal currents, river flows, and storm surge may be important mechanisms for water exchange to include in the simulations when studying different situations. Simulated velocities obtained from the different scenarios were used to calculate the renewal time as a measure of the water exchange (presented in detail in section 7.3). Figures 37 and 38 show the spatial flow pattern within the lagoon system at both inlets for two different time steps during normal inlet conditions (Case 1).

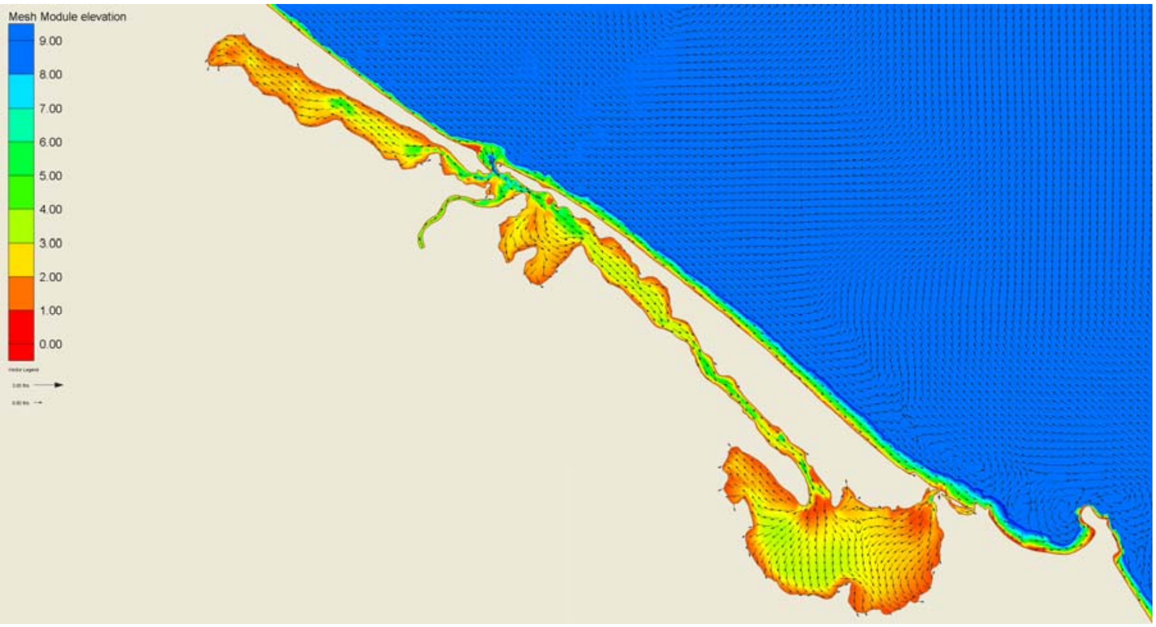


Figure 37 Simulation of tidally induced flow in the lagoon system (incoming flow; time step *t* = 54000 sec)

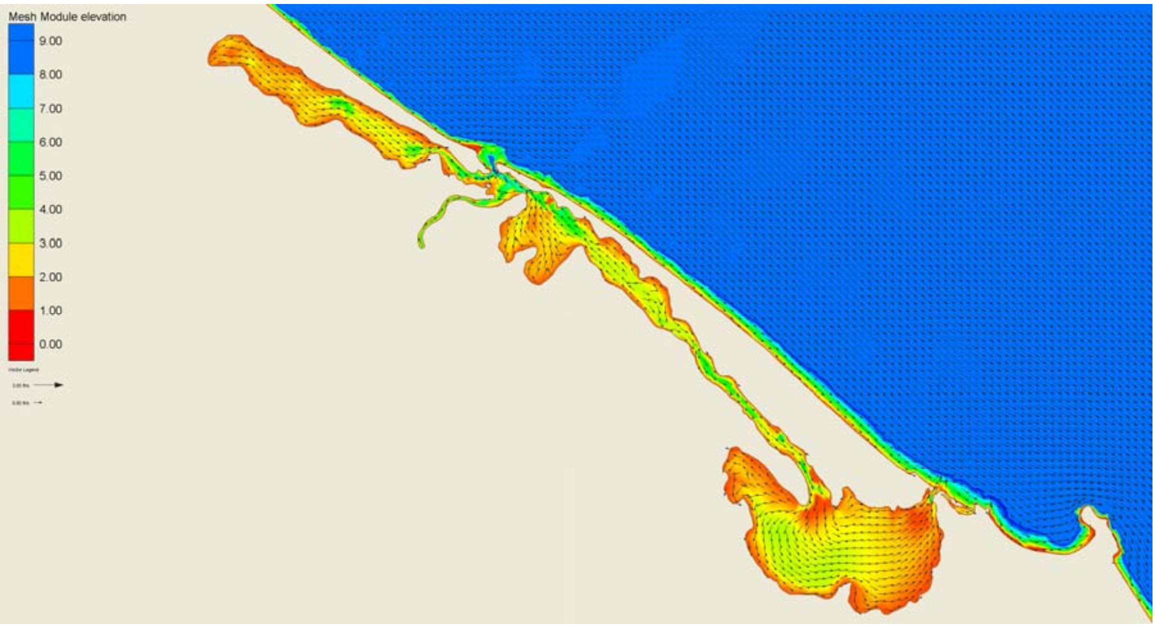


Figure 38 Simulation of tidally induced flow in the lagoon system (outgoing flow; time step *t* = 68400 sec)

7.1 Sensitivity Analysis

Before model simulation for the different scenarios selected, a general sensitivity analysis was performed. The main objectives of this analysis were to assess the influence on the simulation results of changing certain parameter values and to gain insight into model response in preparation for calibration and validation. The model sensitivity to the parameters was investigated by varying their values and calculating the effect on the WSE and velocity at field stations S01 and S02 (outside and inside the lagoon inlet, respectively) for the time period of field measurements in February 2009. The main model parameter studied, and the only one discussed in the report, is the bed friction coefficient (f). As an option, the ADCIRC model may be operated approximating the friction force as being linear ($f \sim v$, where v is the current speed) or quadratic ($f \sim v^2$).

A general, quantitative understanding of the importance of the friction coefficient (f) for the modeling results was gained through the sensitivity analysis. The calculated velocity for different values on the friction coefficient under constant, quadratic frictional resistance in ADCIRC is presented in Figure 39 for S01, where values on f equal to 0.0025, 0.002 and 0.0015 were employed. The simulation results displayed in Figure 39 encompassed a rather short period of time, 92 hrs, but were sufficient to assess the effects of f on the velocity. It is clear that as the value on the friction coefficient increases, the amplitude of the tidally induced velocity is correspondingly dampened. An increasing friction coefficient value overall lowers the velocity, decreasing both the maximum and minimum velocities.

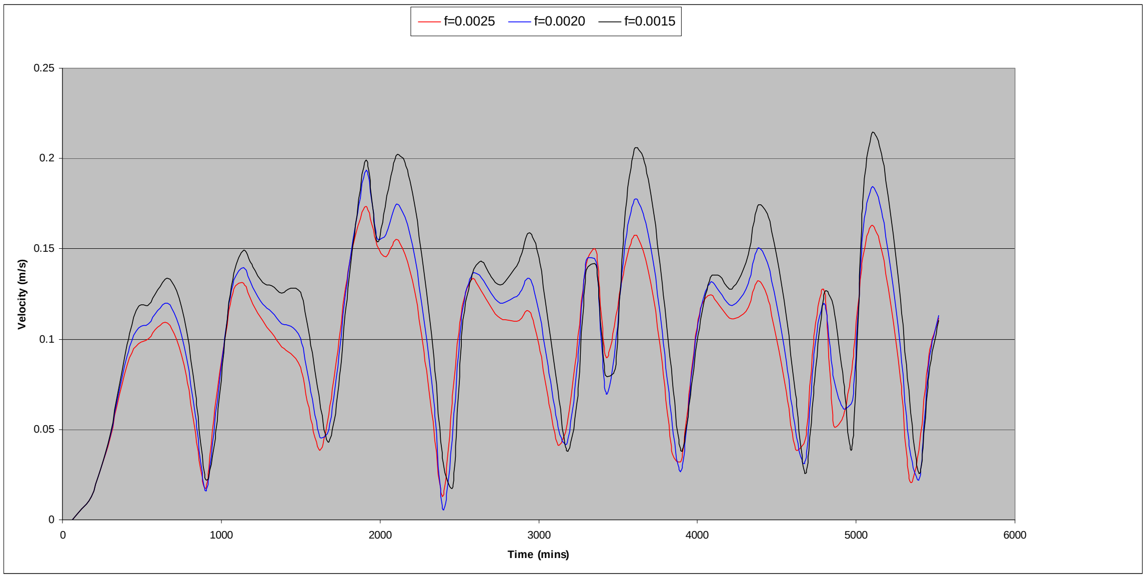


Figure 39 The effect of an increased friction coefficient value on the simulated velocity at field station S01 (outside the lagoon) under constant, quadratic friction forcing in ADCIRC. Friction coefficient values include *f* = 0.0025, 0.002, 0.0015.

Varying the friction coefficient value has a lesser impact on the simulated WSE than on the velocity. Similar sensitivity analysis was performed for the WSE with regard to changing the value of the friction coefficient. Figures 40 and 41 show the effects of varying the friction coefficient value on the simulated WSE at both field study stations (S01 and S02).

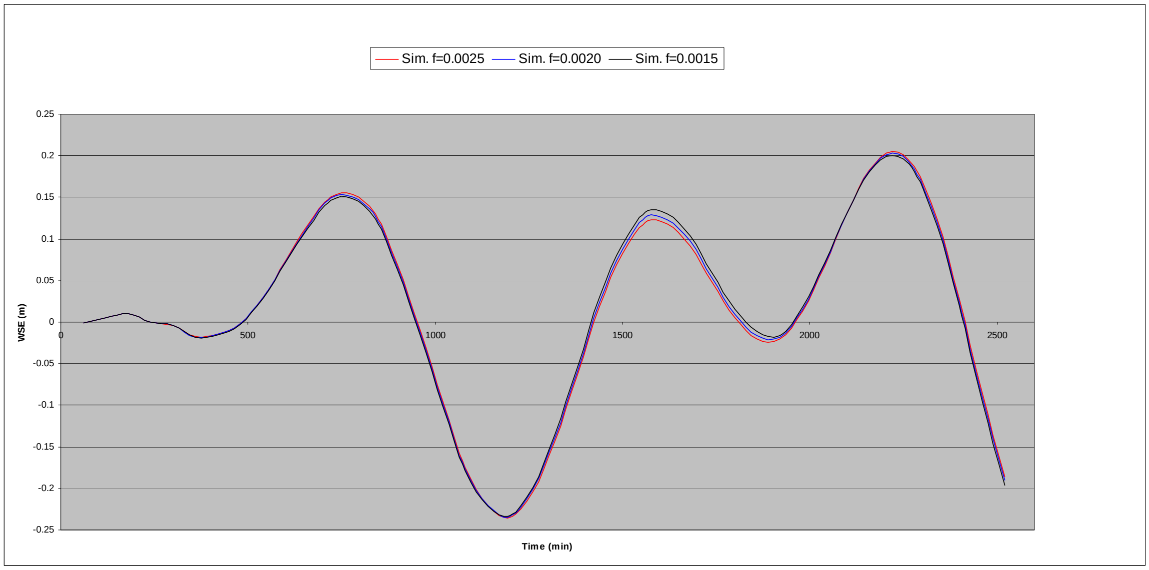


Figure 40 The effect of an increased friction coefficient value on the simulated WSE at field station S01 (outside the lagoon) under constant, quadratic friction forcing in ADCIRC. Friction coefficient values include *f* = 0.0025, 0.002, and 0.0015.

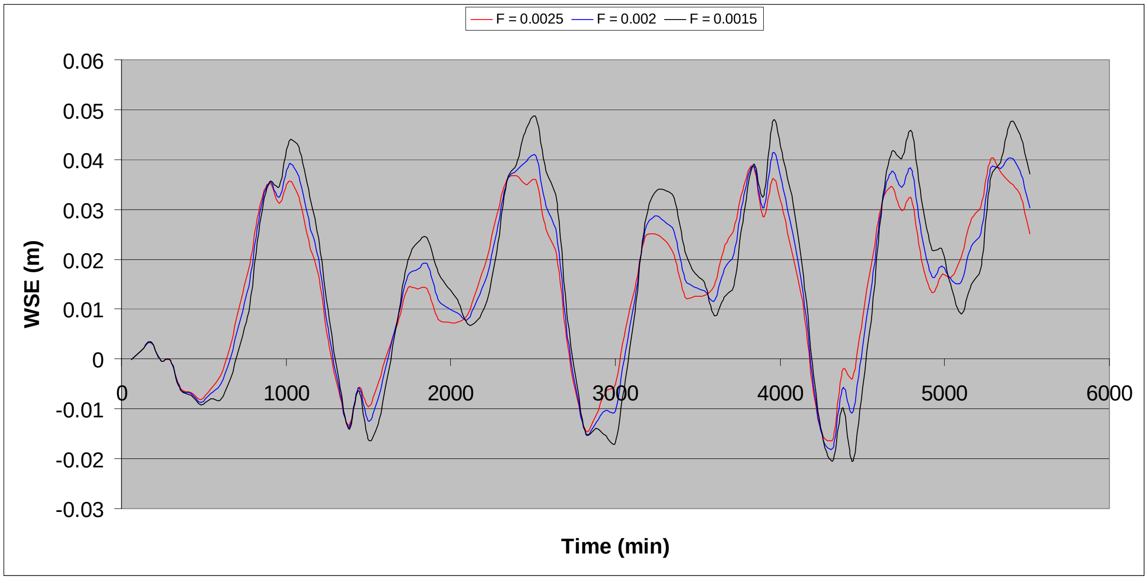


Figure 41 The effect of an increased friction coefficient value on the simulated WSE at field station S02 (inside the lagoon) under constant, quadratic friction forcing in ADCIRC. Friction coefficient values include *f* = 0.0025, 0.002, and 0.0015.).

Sensitivity analysis with respect to the friction coefficient showed a large influence on the velocities. ADCIRC under SMS version 10.0 allows the user to specify the calculations of the bottom friction in several different ways. In the present analysis, constant linear and constant quadratic frictional resistance was investigated. The difference between these two formulations is how the friction grows with respect to the velocity. Under laminar flow conditions, friction is directly proportional to velocity ($f \sim v$), however, these conditions normally do not prevail in a lagoon or the open sea, although it might be convenient from a numerical point of view to apply a linear friction. In the present situation the flow is turbulent and the friction is approximately proportional to the square of velocity ($f \sim v^2$). The result of applying a linear or quadratic model of the frictional forces for the velocity at S01 are illustrated in Figure 42.

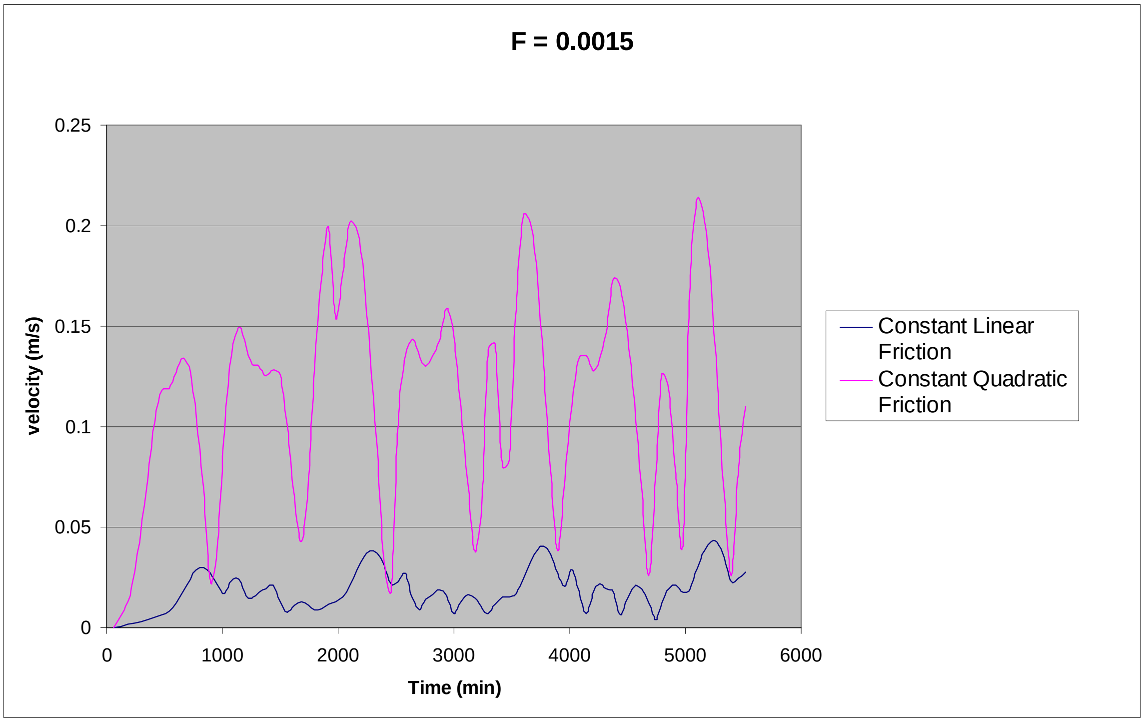


Figure 42 The effect on the simulated velocity at field station S01 (outside of lagoon) when applying constant linear and constant quadratic frictional forcing in ADCIRC.

If the same coefficient value is employed for constant linear and constant quadratic frictional resistance in ADCIRC the effect on the simulated velocity is large. A constant linear friction strongly dampens the amplitudes of the simulated velocity in comparison to that of a constant quadratic friction. Overall, a smoother velocity variation is obtained for the linear case. In practice, if a linear friction description is used a smaller coefficient values would be selected for the present case to compensate for the stronger dampening of the velocity when comparisons are made with data.

7.2 Model Calibration and Validation

After the sensitivity analysis, an effort was made to validate the model, that is, to show that the model can simulate the flows in the lagoon system. In this process, certain model parameter values are selected by comparing simulated results with measured data (calibration), after which an independent data set is used to check the calibrated parameter values (verification). In the present case, since the area of importance for water exchange is defined by the inlet conditions, the calibration of the model was focused on field station S02, inside of the lagoon near the inlet mouth. Also, at this station the tidal current would dominate the flow, whereas at S01 some effects from coastal currents generated by other mechanisms are expected. Model tests were run with varying values on the friction coefficient and the simulation results were compared with the measured data. A quadratic description of the frictional resistance was employed since this was most realistic for the flow conditions under study.

Only a limited data set was obtained during the field campaign and these data were employed in the calibration processes. Thus, data were not really available for verification, and in order to make the validation more solid the calibration process focused on standard values recommended in the ADCIRC manual. If these standard values produce acceptable simulation results, the general model applicability should be ensured.

The standard value on the frictional coefficient in ADCIRC is $f = 0.0025$, however, tests were run with varying coefficient values in order to see the effect on the simulated velocities. Figure 43 shows the result of the simulations with the different friction coefficient values together with the measured velocity at S02 (compare Figure 36). Because of the spin-up period in the calculations the initial part of the measured data was not included.

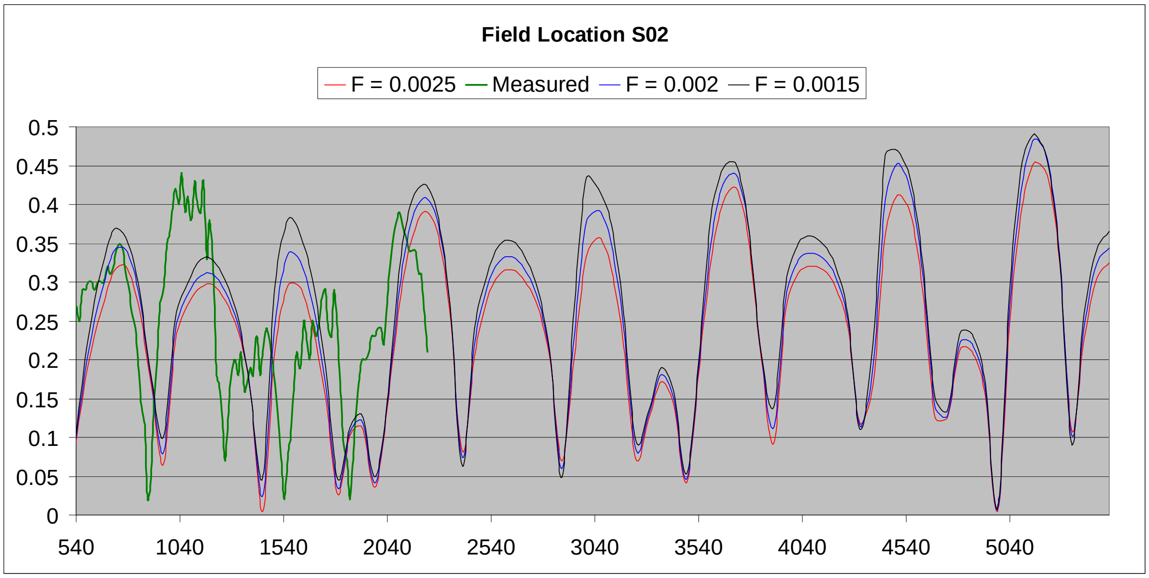


Figure 43 The effect of different friction coefficient values on simulated velocity at S02 (inside the lagoon) compared to the measured velocity under constant, quadratic frictional forcing in ADCIRC (friction coefficient values include *f* = 0.0025, 0.002, and 0.0015).

Inspection of the simulated and measured velocities, as seen in Figure 43, gives insight to the sensitivity towards the selected friction coefficient values. A value of $f = 0.0025$, the same value set as default by ADCIRC, was ultimately chosen as the optimum value for the friction coefficient that overall best reproduced the observed results at field station S02 (result shown in Figure 44). Although some of the other coefficient values provided less discrepancy from the measurements compared to the selected value for specific time periods, overall $f = 0.0025$ provided the best fit over the entire time period of measurements. Also, because ADCIRC recommends $f = 0.0025$ as the default value on the friction coefficient there is support that this is more likely an acceptable value to be employed than the others, thus indirectly validating the model application to the lagoon system.

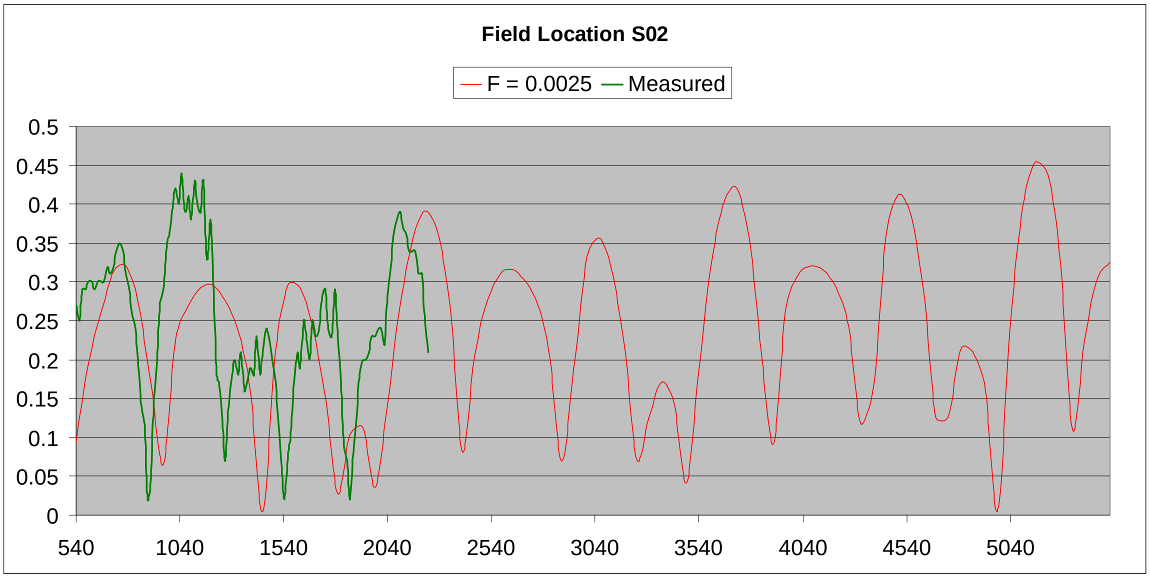


Figure 44 Simulated velocity with ADCIRC versus measured velocity at field station S02 under constant, quadratic frictional forcing (the selected value on the friction coefficient used that produced best agreement corresponded to the default value in ADCIRC *f* = 0.0025)

7.3 Simulation of Scenarios

An in-depth analysis of the selected scenarios is presented in this section, and the resulting water exchange are illustrated for each case and compared with the control case (Case 1: both inlets open). The water exchange through the inlet was determined using the continuity equation at the inlet mouth expressed as,

$$Q = VA \qquad \text{Equation 8}$$

where Q is the volume flow, V the mean velocity across the inlet, and A the cross-sectional area. The flow calculations were made based on the simulation results from ADCIRC using several points along an observation line across the inlet mouths in order to get an estimate of the flow in and out of the lagoon as induced by the tide. The total length of the observation lines at the Thuan An and Tu Hien inlets, approximately 630m and 100m, respectively, were divided into small sections of approximately 1m width in order to increase flow calculation accuracy when integrating for the total flow and exchange volumes. Simulated values on the local velocity were employed at each point along the observation line, together with inlet depths and the distance between observation points. The distances between neighboring points, dividing the observation line into equal segments, were multiplied with the depths in order to obtain the cross-sectional area for each segment in the flow calculations. This process was employed for each point along the observation line at each time step, creating a time series of total exchange flows over the simulation period. In this manner, calculation of the tidal flows was performed for a period of 92 hr. Figure 45 illustrates an observation line put across the Thuan An inlet for the purpose of computing exchange flows.

After the time series of exchange flows had been calculated, the total flow volume passing through the inlets during a tidal cycle was determined through integration in time. The net volume of flow through the inlets in both directions was determined for a number of tidal cycles and compared for each scenario. Both the average and net volumes exchanged were calculated for each inlet and scenario with respect to a number of tidal cycles, as explained later in this section. Table 6 shows the basic geometric properties of the lagoon system, common to all cases studied.

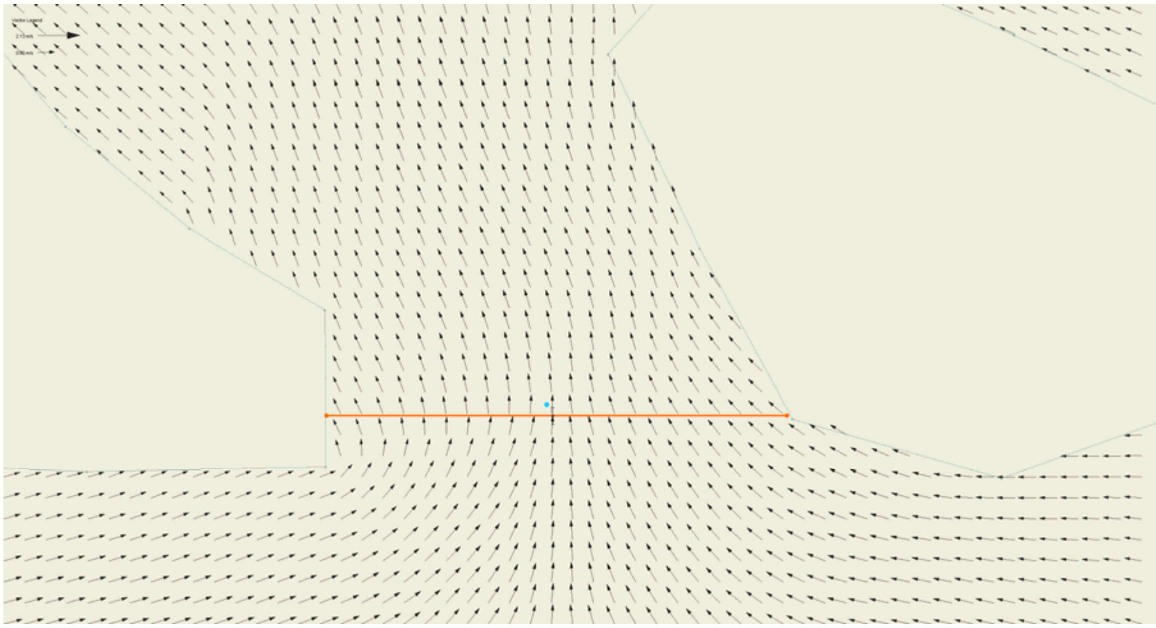


Figure 45 Instantaneous velocity field at Thuan An inlet (time step 115200 sec), together with observation line, used to calculate volumetric flows and exchange volumes through the inlets

Table 6 Lagoon geometric properties

Lagoon Property	
Area (10^6 m^2)	216
Mean Depth (m)	1.4
Volume (10^6 m^3)	300

7.3.1 Case 1 – Normal Inlet Conditions

Exchange flows were calculated for Case 1, where both inlets were open, based on the output values every 60 minutes from ADCIRC. In the time integration, these values were used for interpolated to obtain values every 5 minutes and from those values the average and net exchange volumes were computed for each inlet. These volumes were calculated at each inlet for the same tidal cycles in order to facilitate comparison of the volumes. Table 7 summarizes the calculated exchange volumes for Case 1.

Table 7 Calculated exchange volumes for Case 1 at the studied inlets (volumes in m^3)

	Avg. Exchange Volume	Net Exchange Volume
Thuan An Inlet	$26.9\ 10^6$	$1.2\ 10^6$
Tu Hien Inlet	$4.4\ 10^6$	$0.4\ 10^6$
Total Lagoon Water Exchange	$31.3\ 10^6$	$1.6\ 10^6$

Figures 46 and 47 show inlet bathymetry with respect to the observation lines used to derive velocities at Tu Hien inlet and Thuan An inlet, respectively, at approximately 1 meter intervals in order to compute the exchange flows and volumes through the inlets. Inlet width at Tu Hien in comparison to Thuan An is a lot smaller, about 1/6; thus, the water exchange through Tu Hien inlet is expected to be considerably lower than at Thuan An inlet based on different inlet geometry and similar tidal forcing. Table 7 shows that this is indeed the case.

The average exchange volume represents the volume of water that is exchanged a during tidal cycle (*e.g*., the tidal prism). This volume was estimated as an average for the tidal cycles included in the simulations encompassing 92 hr of data, which corresponds to about 7 cycles. Both the inflowing and the outflowing volumes during a tidal cycle was employed in the averaging. Because a limited number of tidal cycles were studied, some residual volume was obtained when the inflowing and outflowing water was summarized for the inlet, in Table 7 denoted as the net exchanged volume. Over a long-term period, and with a high accuracy in the integrated exchange volumes, this net exchange volume should be zero. In the present case the net exchange volume is 5-10% of the average exchange volume. This percentage might be taken as the accuracy in the estimate of the average exchange volume for the studied period.

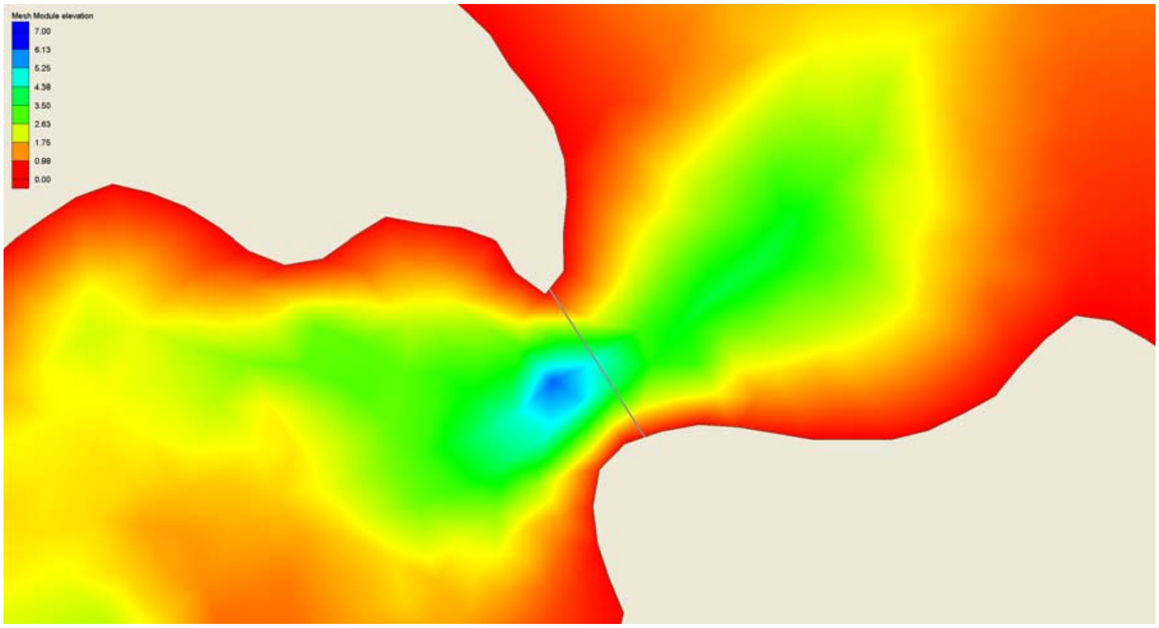


Figure 46 Tu Hien Inlet and employed observation line used to calculate exchange flows and volumes for Case 1

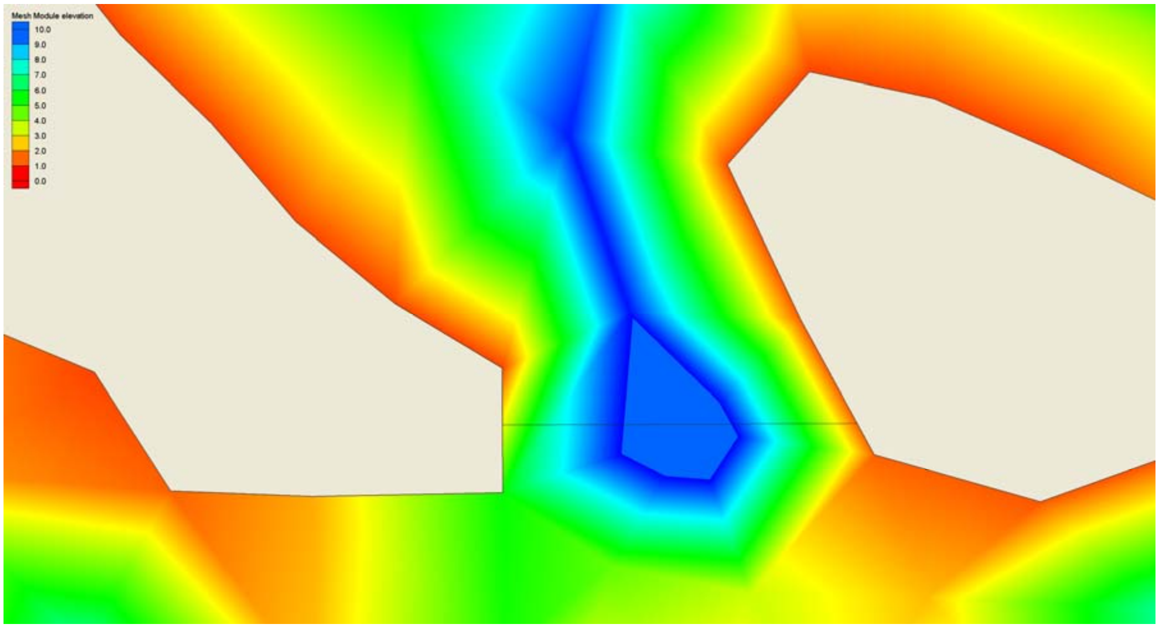


Figure 47 Thuan An Inlet and employed observation line used to calculate exchange flows and volumes for Case 1

7.3.2 Case 2 – Partially Closed Tu Hien Inlet

Case 2 illustrates the effect of sand spit aggregation at Tu Hien inlet on the water exchange between the Tam Giang-Cau Hai lagoon system and the South China Sea. Figure 16 qualitatively shows the assumed spit development at Tu Hien inlet for Case 2, inducing a partial closure that primarily affects the water exchange in the Cau Hai lagoon, although some influence occurs also on the water exchange through Thuan An inlet. The width of Tu Hien inlet was about 1/3-closed in the this scenario.

The coastline presented in Figure 48, including the growing sand spit at the Tu Hien inlet, was generated based on an estimate of how the sand spit would develop using observations on spit growth in the past (compare Figure 13). The addition of the sand spit changes the bathymetry of the inlet; therefore extrapolation of the inlet depths near the sand spit was employed to more accurately represent the affects of the growing spit on the inlet bathymetry, which influences the water exchange. The depths near the sand spit may somewhat differ in reality from the depths used in the simulation, however due to the lack of accurate bathymetrical data taken during spit growth it was the most accurate approach.

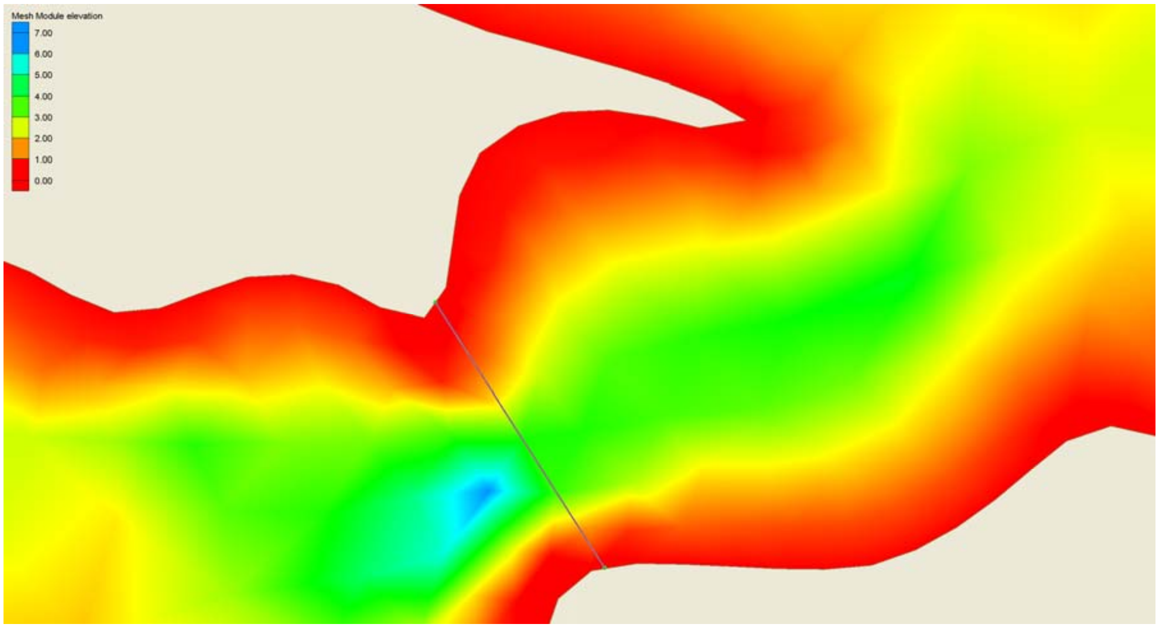


Figure 48 Tu Hien Inlet and employed observation line used to calculate exchange flows and volumes for Case 2

Again, simulated velocities were employed approximately 1 meter apart along the observation lines at each inlet in order to estimate the exchange flow through the inlets. Interpolation of the data at 5 minute intervals was carried out to increase the accuracy of the exchange flow and volume calculations. The resulting values for the average and net volumes exchanged at each inlet for the partially closed scenario (Case 2) is given in Table 8.

Table 8 Calculated exchange volumes for Case 2 at the studied inlets (volumes in m^3)

	Avg. Exchanged Volume	Net Exchanged Volume
Thuan An Inlet	27.9 10^6	2.6 10^6
Tu Hien Inlet	3.9 10^6	0.08 10^6
Total Lagoon Water Exchange	31.8 10^6	2.7 10^6

7.3.3 Case 3 – Fully Closed Tu Hien Inlet

Case 3 represents the final stage of the inlet migration cycle observed at Tu Hien (Figure 49). The inlet mouth at Tu Hien was completely closed off and inlet depths were extrapolated based on the general properties of the morphology at the site and observed spit behavior at closure. It was assumed that during the closure process at the inlet, the adjacent depths would decrease due to the sedimentation and produce a bathymetry with gradually increasing depths away from the inlet in agreement with the typical slope conditions in the area.

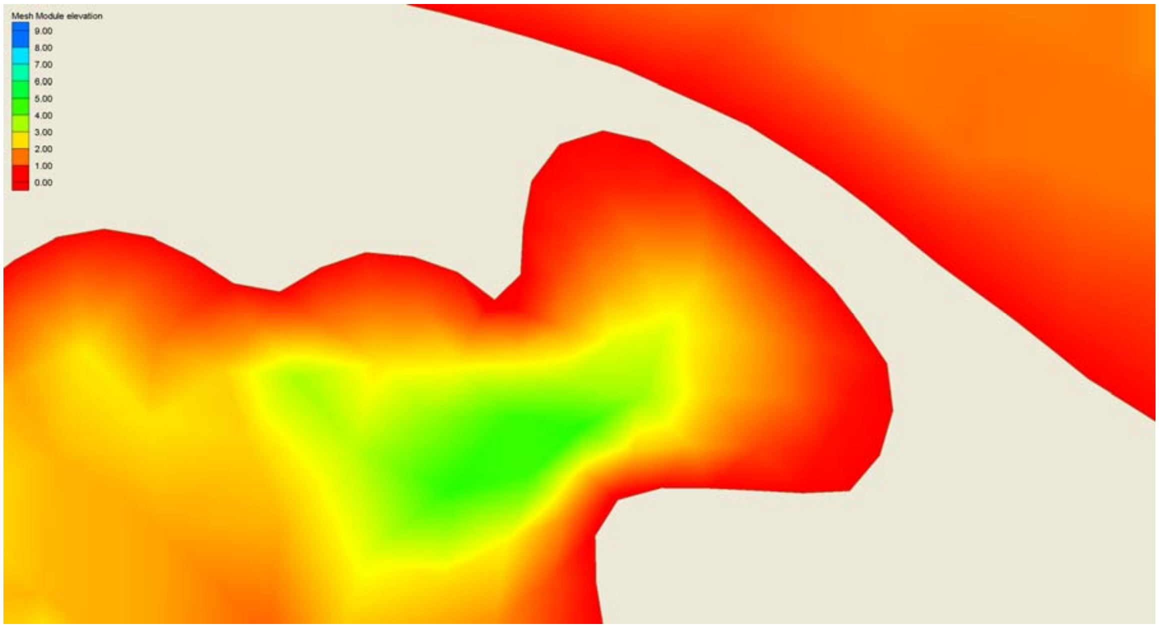


Figure 49 A closed Tu Hien inlet employed in Case 3 to simulate water exchange between the lagoon system and the sea

Table 9 summarizes calculated values for both the average and net exchange volumes between the inlets and the sea. These values were obtained as before by using the velocities simulated at each point along the observation line spanning the inlets. The average and net exchange volumes exchanged were obtained from integration in space (over the inlet cross sections) and time (over a number of tidal cycles). In this scenario there is no exchange between the Tu Hien inlet and the South China Sea since the inlet is completely closed; therefore the entire water exchange between the lagoon system and the sea occurs through the Thuan An inlet.

Table 9 Calculated exchange volumes for Case 3 at the studied inlets (volumes in m^3)

	Avg. Exchanged Volume	Net Exchanged Volume
Thuan An Inlet	$29.0\ 10^6$	$2.7\ 10^6$
Tu Hien Inlet	0	0
Total Lagoon Water Exchange	$29.0\ 10^6$	$2.7\ 10^6$

8 Conclusions

Analysis of the previous three simulated scenarios was employed to assess the effects of changes in Tu Hien inlet on the water exchange between the Tam Giang-Cau Hai lagoon system and the sea. In general, the differences in water exchange between the northern lagoon at Tam Giang and the more southern lagoon at Cau Hai are due to both geometric properties and the forcing conditions, although the former dominates in the present simulations. The northern inlet, Thuan An, which controls the exchange between the Tam Giang lagoon and the sea, has a substantially larger cross-sectional area than the southern inlet, Tu Hien, which determines the exchange for the Cau Hai lagoon. Because of the difference in inlet widths (Thuan An inlet is approximately 6 times wider than Tu Hien inlet) there is a significant difference in the volume flow observed through each inlet. Based on the simulated average exchange volume at the inlets for each case studied, the total flow through the Thuan An inlet is about one order of magnitude larger than that passing through the Tu Hien inlet. Thus, the simulations show that, although the Tu Hien inlet is more influenced with respect to changes in morphology, the Thuan An inlet is responsible for the most of the overall flushing of the lagoon system.

However, inspection of each lagoon separately provides a better understanding of the factors that control the renewal time for each lagoon and the quantity of water exchanged for the different scenarios. Due to limited elevation differences between the lagoon surfaces, as well as the narrow channel connecting them, each lagoon acts almost independently of the other with regard to the water exchange with the sea (Lam *et al.*, 2007a), if normal conditions apply (Case 1). If this assumption is employed, then the water exchange between each lagoon and the sea depends only on the local parameters of that lagoon. The renewal time (see Section 4.3.3) for the Tam Giang lagoon will be much lower (2.0 days for Case 1) than for the Cau Hai lagoon (10.4 days for Case 1) for all of the studied scenarios. The difference between the lagoons will become larger as the Tu Hien inlet approaches closure and water exchange between the Cau Hai lagoon and the sea through this inlet decreases towards zero.

The analysis of the water exchange between the lagoon system and the sea is of primary interest because of the importance for the environmental conditions. It is obvious that a lower renewal time will result in better flushing of the lagoon system, which in turn reduces the effects that pollutants released within the lagoon will have on the habitat. The larger width of the Thuan An inlet, implying a larger exchange flow, allows for a lower renewal time for the Tam Giang lagoon, making it more resistant to pollutants (if considered separately from the Cau Hai lagoon). With regard to the more southern lagoon at Cau Hai, the longer renewal time, resulting from a smaller lagoon flow associated with a smaller inlet width, results in a lower ability for the lagoon to flush out pollutants. The effect of a longer renewal time is illustrated by Figures 50 and 51, which displays the typical amount of pollution found near the Tu Hien inlet in the southern lagoon of Cau Hai. Inspecting the situation occurring in Case 1 under normal inlet conditions the ratio of the Cau Hai lagoon's renewal time to that of the Tam Giang lagoon is about 5:1. This ratio increases as the Tu Hien inlet approaches closure and more of the lagoon flushing for Cau Ha relies on the narrow channel connecting it to the Tam Giang lagoon.

Figure 50 Pollution observed in and along the shores of the Tam Giang lagoon near the Tu Hien inlet

Figure 51 Pollution observed in and along the shores of the Tam Giang lagoon near the Tu Hien inlet

In conclusion, the ability of the lagoon system to renew its water is controlled by the inlets and their parameter that determine the exchange flow through these inlets. The simulations performed in this study demonstrate the northern inlet at Thuan An to be most important for the water exchange between the lagoon system and the sea; however, the water exchange at Tu Hien inlet in the south is more susceptible to morphologic changes. Although the Thuan An inlet overall dominates the water exchange between the lagoon system and the sea, the water exchange at Tu Hien inlet is crucial for the southern lagoon (Cau Hai). As Tu Hien inlet closes, the amount of water exchanged between the entire lagoon system and the sea decreases because the Thuan An inlet to the north cannot sufficiently account for the loss of water exchanged through a completely closed Tu Hien inlet. Water exchange for the lagoon system is concluded to depend mainly on Thuan An inlet to the north; however the water exchange is decreased when Tu Hien inlet closes, and the consequences for the Cau Hai lagoon are considerable.

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