



**A Preliminary Study on Hydrodynamics of the Tam Giang - Cau Hai
Lagoon and Tidal Inlet System in the Thua Thien-Hue Province,
Vietnam**

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A Preliminary Study on Hydrodynamics of the Tam Giang - Cau Hai Lagoon and Tidal Inlet System in Thua Thien-Hue Province, Vietnam

Master of Science Thesis
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ABSTRACT

The Tam Giang-Cau Hai lagoon is the most important coastal lagoon of Vietnam located in Thua Thien-Hue province. Basically formed in the late Holocene (more than 2000 years ago), the lagoon is being in the development stage. Its tidal inlets, nowadays are the Thuan An and Tu Hien inlets, are dynamic and ephemeral morphological features. Inlet migration and shoal, breakthrough of the sand barrier, erosion of beaches and sand dunes affect on socio-economic development and environment of the province to a high degree. Serious consequences of these processes are adverse effects on flooding and inundation, transportation, navigation, fishery, aquaculture, agriculture, lagoon ecosystem and environment.

As a primarily step of research on the system, the study is limited on the hydraulic characteristics of the system with the main objectives are to set-up a numerical model to simulate and investigate the hydraulic behaviour of the system; to evaluate the stability situations of the inlets; and to suggest which processes and data are relevant for the successive steps of the study on morphology of the system.

DUFLOW has been employed to simulate the hydraulic behaviour of the system under different boundary conditions of sea water level, river flow discharge, inlet geometry and configuration. Sensitivities and effect of the uncertainty of sea level rise, storm surges, inlet openings, river flows and tidal parameters on the hydraulic characteristics of the system have been also investigated. Stability of the inlets has been evaluated accordingly.

Model results indicate that river flows are the most important acting force of the system during floods. Tides, storm surges and inlet openings are also important factors changing the hydrodynamic characteristics of the system in these extreme conditions. In the dry season, the most important factors influencing the hydrodynamic characteristics of the system are tides, sea level rise and inlet openings. Tidal water level, river floods, and sediment transport are the most sensitive acting forces influencing the stability of the inlets. The stability situation of the Thuan An inlet is in a “fair to poor” situation, according to Brunn’s P/M_{tot} criterion. The Tu Hien inlet, which is relatively independent with the openings of other inlets, is always in a “poor” stability condition.

Beside of using the model for hydrodynamic simulation of the whole system, it is recommended to employ a morphologic model (preferably 2D) in the successive steps of the study for in detail simulation of the inlets and their vicinity taking into account of effects of tides, waves, river flows, flow circular by wind, density current, sediment transport. The relevant processes and related data are also recommended for future studies.

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ABBREVIATIONS

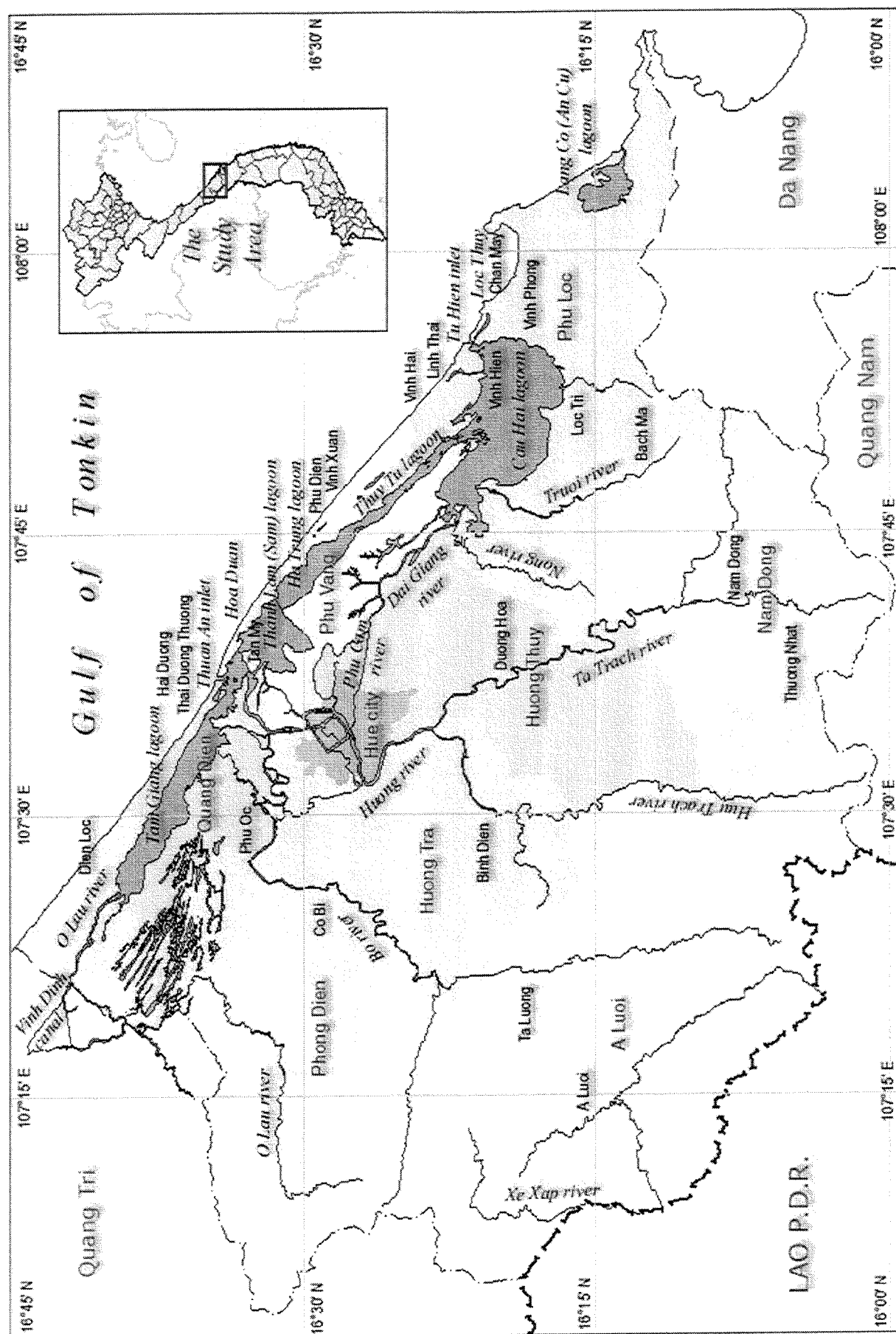
ADB	Asian Development Bank
ASCE	American Society of Civil Engineers
BP	before present
CERC	Coastal Engineering Research Centre
DARD	Thua Thien-Hue Department of Agriculture and Rural Development, Thua Thien-Hue province
DOSTE	Department of Science, Technology and Environment, Thua Thien-Hue province
DUFLOW	Dutch Flow – an 1D numerical model
HAT	Highest Astronomical Tide
HEC1	Hydraulic Engineering Consultant Company No 1, Vietnam
HMS	Vietnam Hydro-Meteorological Services
HWRU	Hanoi Water Resources University
IHE	International Institute for Infrastructural, Hydraulic and Environmental Engineering, Delft, The Netherlands
LAT	Lowest Astronomical Tide
MARD	Ministry of Agriculture and Rural Development
MHW	Mean High Water
MHHW	Mean Higher High Water
MHLW	Mean Higher Low Water
MHWN	Mean High Water Neap
MHWS	Mean High Water Spring
MLHW	Mean Lower High Water
MLLW	Mean Lower Low Water
MLW	Mean Low Water
MLWN	Mean Low Water Neap
MLWS	Mean Low Water Spring
MSL	Mean Sea Level
MOSTE	Ministry of Science, Technology and Environment
RAMSAR	The Convention on Wetlands, signed in Ramsar, Iran, in 1971
SOGREAH	Société Grenobloise d'Etude et d'Applications Hydrauliques
TU Delft	Delft University of Technology, Delft, The Netherlands
UNESCO	United Nations Educational, Scientific and Cultural Organisation
USACE	US Army Corps of Engineers

VIWRR	Vietnam Institute for Water Resources Research
VRSAP	Vietnam Rivers And Flood Plains – a 1D numerical model for flow and salt intrusion
VVA	Vietnam Vulnerability Assessment programme implemented by Marine Hydro-meteorological Center (HMS Vietnam), Polish Academic of Science (Institute of Hydro-engineering, Gdansk, Poland), Joint venture Frederic R Harris BV – Delft Hydraulics (The Hague, The Netherlands) and National Institute for Coastal and Marine Management, Coastal Zone Management Center (Ministry of Transport, Public Works and Water Management, The Hague, The Netherlands).

TABLE OF SYMBOLS

a_o	tidal amplitude in the ocean	(m)
A	cross-sectional flow area	(m^2)
A_B	surface area of the bay or lagoon	(m^2)
A_C	channel cross-sectional flow area	(m^2)
b	cross-sectional flow width	(m)
B	cross-sectional storage width	(m)
C	coefficient of De Chézy	($m^{0.5}/s$)
C'	grain-related Chézy coefficient	($m^{0.5}/s$)
Cr	Courant number	(-)
d_{50}	median particle diameter of bed material	(m)
d_{90}	particle diameter	(m)
D^*	particle diameter parameter	(-)
E_{num}	numerical dispersion	(m^2/s)
f_i	node factor of the constituent i	(-)
F	catchment area	(km^2)
F	the overall impedance of the inlet	(-)
F	form number for tidal classification	(-)
g	acceleration due to gravity	(m/s^2)
g_i	corrected kappa number of the tidal constituent i	(degrees)
h	water depth	(m)
h_C	mean flow depth	(m)
H_i	amplitude of the tidal constituent i	(m)
H_{M2}	amplitude of the M_2 (Semi-diurnal principle lunar tide) constituent	(m)
K	repletion coefficient	(-)
M_{tot}	total littoral drift	($10^6 m^3/year$)
M_{mean}	net littoral drift	($10^6 m^3/year$)
M_{min}	minimum flow	($l/s/km^2$)
M_{month}	minimum monthly flow	($l/s/km^2$)
M_g	littoral drift enters an inlet	($10^6 m^3/year$)
M_0	annual flow	($l/s/km^2$)
n	Manning's roughness coefficient	(-)
P	tidal prism	($10^6 m^3$)
Q	flow discharge	(m^3/s)
Q_0	annual flow	(m^3/s)

$Q_{\max}$	maximum discharge	(m ³ /s)
$Q_{\min}$	minimum discharge	(m ³ /s)
Q_{month}	minimum monthly discharge	(m ³ /s)
R	hydraulic radius	(m)
t	time variable	(sec.)
T	tidal period	(sec.)
T	bed-shear stress parameter	(-)
T_S^*	bed-shear stress	(kg/m ²)
$U_{*,c}$	bed-shear velocity related to current	(m/s)
u_{cr}	critical depth-averaged velocity	(m/s)
v_i+u_i	equilibrium argument of the tidal constituent i	(degrees)
V	cross-section averaged flow velocity	(m/s)
$V_{\max}$	maximum cross-section averaged flow velocity	(m/s)
$V_{\text{mean max}}$	maximum value of cross-sectional averaged flow velocity	(m/s)
V_{mean}	cross-section averaged flow velocity	(m/s)
w	wind speed	(m/s)
W_0	annual flow volume of the catchment	(10 ⁶ m ³)
x	distance measured along channel axis	(m)
Z	water level with respect to the reference level	(m)
Z_0	mean water level	(m)
α	correction factor for non-uniform distribution of the flow velocity in the advection term of the momentum equation in the Saint-Venant's system of equations	(-)
Δt	time step	(sec.)
Δx	space step	(m)
Φ	wind direction	(degrees)
ϕ	direction of channel axis measured clockwise from the north	(degrees)
γ	wind conversion coefficient	(-)
θ	weighting factor of the Preissmann finite difference scheme	(-)
θ'	particle mobility parameter	(-)
θ_{cr}	critical Shields parameter	(-)
ρ_s	solid density of sediment	(kg/m ³)
σ	tidal wave frequency	(radians/hour)
$\tau_{b,cr}$	time-averaged critical bed shear stress	(N/m ²)
$\tau'_{b,c}$	grain-related bed-shear stress	(N/m ²)
ω_i	angular speed of the tidal constituent i	(degrees/hour)



Chapter 1. THE TAM GIANG-CAU HAI LAGOON AND THE ISSUED PROBLEMS

1.1. DESCRIPTION OF THE STUDY AREA

1.1.1. General description of the area

Thua Thien-Hue province is located in the Coastal Central Area of Vietnam. The geographic coordinates of the province are 16°00' – 16°45' North latitude and 107°03' – 108°12' East longitude. The total area of the province is 5,009 km², and the population is more than 1 million people. The provincial economic bases mainly on small industries and handicrafts, tourism and services, agriculture, forestry, aquaculture and fishery.

Thua Thien-Hue province has a great tourism potential. The provincial capital – Hue city was the former imperial capital of Vietnam from 1802 to 1945. It was inscribed on the UNESCO World Heritage List in December 1993. Together with the city of Hue, there are many beautiful landscapes like the Tam Giang – Cau Hai lagoon system and many beautiful beaches such as Thuan An, Lang Co and Canh Duong along the coastline of 120 km of the province making this area becomes one of the most attractive tourist place of the country.

1.1.2. The Tam Giang-Cau Hai lagoon and tidal inlets system

The Tam Giang – Cau Hai lagoon system with an area of about 216 km², is the biggest lagoon in Southeast Asia. The lagoon is being proposed by the Government of Vietnam and Asian Development Bank (ADB) as a Marine Protected Area and a RAMSAR Site for its unique in term of landscape and diversity of biological resources.

The lagoon is a complex system comprised of a series of coastal lagoons that is separated from the sea by narrow sand dune barriers. It is collecting flows of most rivers in the province and discharges to the sea with only two tidal inlets along 68 km of its length. The present inlets of the lagoon are the Thuan An inlet in the north at the position close to the Huong river mouth and the Tu Hien inlet in the south.

The lagoon extends from the O Lau river in the north-west to Vinh Long mountain in the south-east with a length of 68 km. It occupies 4.3% of Thua Thien-Hue province area or 17.2% of the area of the Hue delta. It consists of Tam Giang, Thanh Lam (Sam, An Truyen), Ha Trung, Thuy Tu and Cau Hai lagoons (Truong Van Tuyen and Veronika Brzeski, 1998).

The system is strongly influenced by both marine and inland flow conditions. Interaction of the tides and salt water from the sea influence to the system through the Thuan An and Tu Hien inlets with inland flow discharges of the rivers cause highly dynamic characteristics of hydraulics and morphology.

This lagoon and tidal inlet system has an important role for navigation, fishery, aquaculture, agriculture, and tourism of Thua Thien-Hue province. Not only effects to the socioeconomic development of the province, it also takes a very important function in coastal ecology and environment of the area. It is providing directly sources of living to about 300,000 inhabitants living in the surroundings the lagoon and deeply influences to their survival in term of natural disasters.

The urgent problems of the lagoon, tidal inlets and coastal zone in the province that local people and local authorities have been facing can be stated as in the section following.

1.2. PROBLEM IDENTIFICATION

Under effects of a combination of tides, currents, waves and sediment transport, the development of the lagoon, its inlets, the sand barrier and dunes (including shoaling, inlet migration, breakthrough of the sand barrier and eroding beaches and sand dunes) influences the environment and socio-economic development of the province to a high degree.

The following are the most important processes that contribute to the problems of the lagoon

- Migration of the existing inlets has an adverse effect on navigation. The Thuan An inlet has been migrating its channel northward about 15 m/year since 1931 (Tran Duc Thanh, 1996).
- Sedimentation in the Thuan An inlet and its access channel causes difficulties for navigation and flood evacuation,
- Declination and closure of the Tu Hien inlet block navigation, change salinity of the lagoon, make an obstacle to flood evacuation and increase the possibility of inundation in the lowland areas. Closure of the Tu Hien inlet also reduces the circulation in the Cau Hai lagoon, increases sedimentation and shallow the lagoon that is causing this lagoon to decline.
- Breakthroughs of the sand barrier cause a decline of existing inlets, interrupt transportation and communication between residential areas, change hydrochemical characteristics of the lagoon.
- Coastal erosion of beaches and dunes gives auspicious conditions for breakthroughs of the sand barrier and opening of new inlets.

Effects of these processes have the following consequences:

- Flooding and inundation

The shallowness of the lagoon, the migration and silting up of the inlets, and even sometimes, the closure of the inlets by nature, reduce flood evacuation capacity and increase the possibility of inundation in the area. Inundation of the area has serious consequences such as losses of human life, their properties, livestock, crops, means of production, infrastructure, causes landslides, and environmental pollution.

In flood events of 1983, 237 people have lost their life, 7642 hectares dry crops and 603 hectares paddy were destroyed, 770 hectares of cultivated area was eroded, 1760 cattle were dead. Total economic loss was about 10 billion VND (Le Bac Huynh *et al.*, 1999).

During a big flood in November 1999, 324 people were killed and missing, 212874 houses were flooded and damaged, 45000 hectares of paddy and 5031 hectares of other crops were flooded and destroyed. Total economic loss was about 112 million US dollars (Le Bac Huynh *et al.*, 1999).

- Interruption of transportation and blocking navigation

Breakthroughs of the sand barrier due to typhoons and floods separate and isolate apart of the population living on the sand barrier, and effect on communication between residential areas. The opening of new inlets also causes existing inlet to decline.

The migration and shoal of the inlets have negative effects on the navigation of vessels entering the Tan My harbour and on sheltering from hurricanes inside the lagoon.

The closure of the Tu Hien inlet causes about 300 fishing boats have to travel 40 km more to go fishing in the sea every day. This also increases possibility of vessels sinking in the sea during hurricanes which could not enter the lagoon for sheltering.

- Adverse effects on the lagoon ecosystem and environment

Opening of new inlets or declination of existing inlets will change the hydrochemical characteristics and the biological structure of the lagoon.

Changing salinity of the lagoon has a strong influence on the ecology system and biodiversity of the lagoon. If the salinity reduces, the structure of the biological communities will be changed, the marine ecosystem will disappear and be replaced with freshwater ecosystem which has a lower biomass and production.

- Adverse effects on fishery

The possible closure of the Tu Hien inlet prevents navigation of fishing boats in this inlet and has inverse effects on fishery.

- Adverse effects on aquaculture

Changing salinity also effects on the aquaculture, mainly red algae, sugpo prawn (common tiger prawn), garrupa can not be developed. Every time, when the Tu Hien inlet is closed or opened, the existing aqua farms will be destroyed due to changes of salinity. It will take along time to rehabilitate the aqua farms with new species that are compatible with new situation of salinity.

- Adverse effects on agriculture

Salt intrusion affects on agriculture in the areas surrounding the lagoon and lowland of the Huong and O Lau rivers. The total cultivated area that is effected by salt intrusion is 2000 – 2500 hectares (Tran Dinh Hoi *et al.*, 2001).

1.3. OBJECTIVES OF THE STUDY

As a preliminary step of research on the system, this study is limited and aimed to get acquainted with the hydraulic characteristics of the lagoon and inlet system under the combined effects of tides and river flows.

The main objectives of the study are

1. To set-up a numerical model to simulate and investigate the hydraulic behaviour of the system under different boundary conditions of sea water level, river flow discharge, inlet geometry and configuration.
2. To evaluate the stability situations of the inlets.
3. To evaluate the data available and to suggest which processes and related data are required to be observed more for the further study on morphology of the lagoon, tidal inlets and the coastal area including effects of waves, storm surges, tides, density currents, river floods, sediment transport and salt intrusion in the whole system.

1.4. SCOPES OF THE STUDY

Due to the data available are limited, the study is restricted on the on the hydrodynamics of the lagoons and tidal inlets. The main factors affect the system included in this study are sea water level (tides, sea level rise, storm surges), river flows, and inlet openings. Effects of wind, waves, long-shore currents, density currents, salt intrusion, water quality, sediment transport, and morphological processes are not taken into account. Mechanisms of inlet migration and shoal, breakthroughs, and morphology of beaches and dunes are not the targets of this study. Socio-economic and environmental aspects are not taken into the consideration in this study.

The study is focused only on the Tam Giang-Cau Hai lagoon and tidal inlets. The relationship of the system with the morphology of the shoreline will not be considered. The relationship of the lagoon and tidal inlet system with the river system are interested only in term of inflows from rivers to the lagoon.

1.5. METHODOLOGY AND APPROACH OF THE STUDY

The methodology of this study is developed based on the characteristics of the Tam Giang-Cau Hai lagoon system and the study area, the knowledge and experiences of the past researches on coastal lagoon and tidal inlets as presented in Chapter 2 and Chapter 3. With the purpose as a reconnaissance level of the study on the hydrodynamics of the Tam Giang-Cau Hai lagoon and tidal inlet system, DUFLOW model tool is chosen and the following approach forms the methodology to achieve the objectives of the study:

1. Literature study to search for literature base concerning lagoons and tidal inlets, and technical information may be available for the study area. Base on previous researches on the study area or similar cases, the possible processes governing the system and related data are recognised.
2. Collect the basic data of geometry and bathymetry of the lagoons and tidal inlets; topography and cross sections of the rivers; tidal water levels; flow discharges, flow velocities and water levels in the rivers and in the system of lagoons and tidal inlets; information about waves and sediment transports.
3. Analyse and process collected data to create boundary conditions for the numerical model.
4. Determine the model domain base on the basic data available for study and characteristics of the study area.

5. Set-up the model based on the basic data, the boundary conditions and the domain of interest.
6. Calibrate the model to determine model parameters.
7. Validate the model with concerning to the uncertainty of the boundary conditions to ensure the model parameters are appropriate.
8. Set up the set of computational scenarios based on possible cases of boundary conditions and simulate the behaviour of the system under the effects of governing factors to investigate the sensitivity of the governing factors.
9. Evaluate the stability of the inlets based on the model results of hydrodynamics.

These steps of the approach are used through the contents of Chapter 4 to Chapter 6.

Chapter 2. GENERAL DESCRIPTION OF THE TAM GIANG-CAU HAI LAGOON AND COASTAL INLETS

2.1. THE FORMATION AND DEVELOPMENT OF THE LAGOON

2.1.1. The conditions for the formation of the system

The Tam Giang-Cau Hai lagoon is located at the edge of the Hue delta. The lagoon has developed on the modern tectonic foundation that was weakly uplifting and transiting with depressions of the continental shelf. The weak tectonic uplift of the Hue delta in the situation of eustatic sea level change was slowed down in the late half of the Flandrian transgression (between 7000 and 3000 years BP) caused the local sea level in the area was relative stable or was very slowly rising. This was a premise for the formation of the lagoons and sand barriers on the outspread and gradually sloping surface of the ancient alluvial delta of Hue in the Pleistocene (10000 – 1.6 million years BP). In these conditions, the formation of a new lagoon to replace the existing lagoon is almost impossible (Tran Duc Thanh *et al.*, 2000).

According to Tran Duc Thanh (Tran Duc Thanh *et al.*, 2000), during the mid-Holocene (about 6000 years ago), the transgression was highest and then slowed down. Sedimentation processes have actively formed the Hue delta, ancient sand dunes and ancient lagoons. These ancient lagoons then declined leaving many remains as freshwater pools and ponds in the Quang Dien and Phu Vang districts nowadays. The auspicious conditions for the ancient lagoons to be rapidly filled with sedimentation were: eustatic sea level change slowed down, the continental shelf was shallow with a gradual slope, and the alluvia sediment were present in high quantities due to cross shore transport.

The sediment source for the formation of the lagoons and sand barriers, as explained by Zenkovitch (1963), was from the ancient Red River and was deposited in the delta in the Gulf of Tonkin in the Pleistocene when the sea level was 100 m lower than the present level. During sea level rises, wave induced sediment transport brought material to the Thua Thien-Hue coast.

In the late Holocene (about 3000 years BP), the coast was moved seaward to the present coastline (due to depositional regression, i.e. the movement of the coastline seaward due to deposition of beaches). But above auspicious conditions were still remains to form the Tam Giang-Cau Hai lagoon and sand dune system. The Tam Giang-Cau Hai lagoon is much greater than the ancient lagoons and may last longer.

River and river-marine sediments are the main materials to form the marshes and tidal flats of the lagoon.

2.1.2. The formation and evolution process of the system

The evolution process of the lagoon can be divided into three stages of initial, young and development stages as followings (Tran Duc Thanh *et al.*, 2000)

2.1.2.1. *The initial stage*

In the initial stage, the lagoon was formed by the development of a sand bar system north-westward in front of a shallow sea area from Linh Thai to Cua Viet (Quang Tri province). The sedimentation by the littoral drift connected the sand bars. The only gaps were the openings at Vinh Hai (north Linh Thai mountain) and Thai Duong Thuong (near Thai Duong Ha) (Krempf, 1931). This stage finished when the sand barrier (named Dai Truong Sa) had fully developed from Linh Thai to Cua Viet. Both inlets then closed by the sand barrier and a new inlet was opened at Tu Hien.

2.1.2.2. *The young stage*

During the young stage, the lagoon had only one inlet named Tu Dung that is the Tu Hien inlet nowadays. The lagoon has received water from almost all rivers of the province (except the Xe Xap River) such as O Lau, Bo, Ta Trach, Huu Trach, Huong, Dai Giang, Nong, Truoi and Cau Hai rivers. These rivers have not played any role in the formation of the lagoon but they have an important function in the development of the system together with the ocean and the late tectonic activities. The young stage is characterised by the relative unique features of the system and the homogeneously and stable development of its components.

2.1.2.3. *The developed stage*

After the young stage, the system got in the development stage that started with a breakthrough of the sand barrier to open the Thuan An inlet in 1404. In fact, this is the declination stage of the system (Tran Duc Thanh *et al.*, 1996). The development stage is characterised by the differentiation in the development of each individual lagoon in the system. The relatively unique features and the stability of the components were broken. The lagoons have been shoaled, narrowed and separated each other into three parts: Tam Giang lagoon, Thuy Tu lagoon and Cau Hai lagoon. These lagoons have been different in flow circulation, morphology, sedimentation and bio-ecology. To get in this stage, the system has come across a geologic evolution and has been influenced by internal and external processes. These processes include three phases (Tran Duc Thanh *et al.*, 1996):

- (1) The development of a fault system caused the obstruction and decline of the Phu Cam River and warning the decline of the Tu Hien inlet. Some other important changes occurred including: the Bo river completely joined to the Huong River and the O Lau River changed its flow direction to discharge into the Tam Giang lagoon (see Figure I.1 and Figure I.2 in Appendix I).
- (2) The development of the ebb-tidal delta in south of the Thuy Tu lagoon and the alluvial benches (terrace) in the Thuy Tu and Tam Giang lagoons created an obstacle to separate the Cau Hai lagoon with others. The development of this ebb-tidal delta has already finished but the obstacle to the flood evacuation causes floodwater to be blocked downstream of the Huong River.
- (3) The delta at the Huong river mouth has been developing rapidly since the development of the sand barrier and the obstacle south of the Thuy Tu lagoon. The channel from the Huong river to the Thuy Tu lagoon has been narrowed. Again, the flood evacuation capacity of the channel has been reduced causing a breakthrough of the sand barrier and opening the Thuan An inlet during the extreme flood event of 1404.

In relatively modern times, human activities have had also important effects on the natural development of the system. These activities include the urbanisation in the Huong riverine area, digging the Vinh Dinh (Vinh Te?) canal to connect the O Lau River and the Thach Han River (Quang Tri province), dredging the Phu Cam River, construction of the Thanh Ha harbour (an ancient port near Bao Vinh) and Tan My harbour, constructions of dikes, salt intrusion preventing weirs, dams and reservoirs, deforestation, development of shrimp farms in the lagoons and man-made closure of inlets.

2.2. THE STRUCTURE OF THE TAM GIANG-CAU HAI LAGOON SYSTEM

According to Nguyen Huu Cu (1995), the Tam Giang-Cau Hai lagoon system can be divided into four basic structural morphological types of components: (1) water body (lagoons); (2) sand barriers; (3) inlets and (4) inland lagoon banks (or sheltered shore).

2.2.1. The water body

The water body of the Tam Giang–Cau Hai lagoon spreads over an area of 216 km² with a length of 68 km. It has an average volume of 300 million m³, or over 400 million m³ when flood waters enter the system. The system can be divided into four different components, namely the Tam Giang lagoon, the Thanh Lam lagoon, the Thuy Tu lagoon and the Cau Hai lagoon. Descriptions of the lagoon geometric features are as follows:

2.2.1.1. *The Tam Giang lagoon*

The Tam Giang lagoon has a length of about 27 km from the O Lau river mouth to the Huong River mouth. It has average width of 2 km, maximum width of 3.5 km and a minimum width of 0.6 km. The area of the lagoon covers 52 km². The average depth of the lagoon is 2 m. There is an ebb channel with a depth 4 to 5 m from the middle of the lagoon to the Thuan An inlet.

2.2.1.2. *The Thanh Lam lagoon*

The Thanh Lam lagoon covers an area of 16.2 km². It includes Sam and An Truyen lagoons. At the north-eastern part of the lagoon, the average depth of the lagoon is 1.5 m. There is an ebb channel north-westward with a depth of 2 to 5 m. At the north-western part of the lagoon, the lagoon bottom is quite even and flat with an average depth of 0.5 m.

2.2.1.3. *The Thuy Tu lagoon*

The Thuy Tu and Ha Trung lagoons have a total length of 24 km with an averaged width of 1 km. The area of the lagoon covers 36 km². The average depth of the lagoon is 2 m. The lagoon becomes deeper closer to the Cau Hai lagoon. The maximum depth of the lagoon is 4 m at Ha Trung. It used to be an ebb tidal channel before the opening of the Thuan An inlet (Tran Duc Thanh *et al.*, 2000). As can be seen in Figure 2.1, there is still an ebb tidal delta in the northern part of the Cau Hai lagoon.

2.2.1.4. *The Cau Hai lagoon*

The Cau Hai lagoon has a shape of a semicircle. The length of the lagoon in the north west – south east direction from Thuy Tu to Vinh Phong mountain is 11 km. The area of the lagoon

is 112 km². The average depth of the lagoon varies from 1 m to 1.5 m increasing westward. The maximum depth is 2 m.

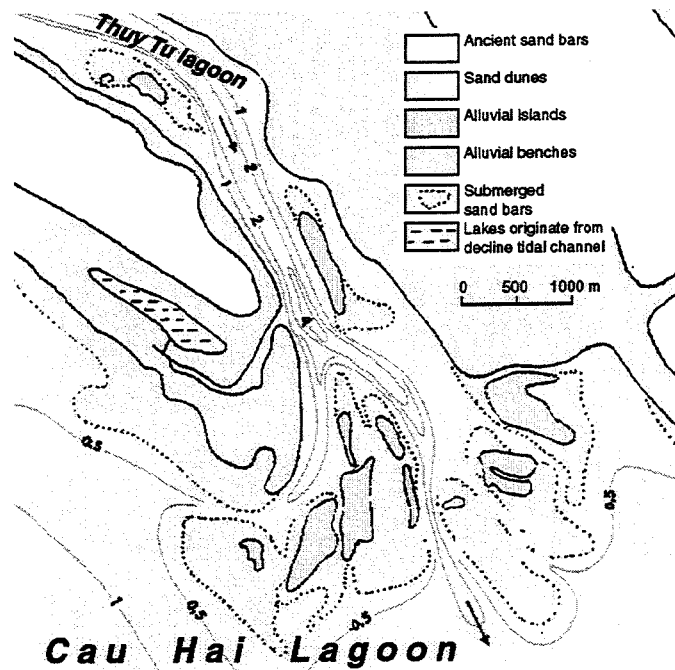


Figure 2.1. The ebb-tidal delta in the south of the Thuy Tu lagoon (after Nguyen Huu Cu, 1996)

2.2.2. The tidal inlets

At present, the Tam Giang-Cau Hai lagoon has two tidal inlets at Thuan An and Tu Hien. The distance between these inlet is 40 km. Since 1404, Thuan An has become the main inlet.

2.2.2.1. The Tu Hien inlet

For centuries, the system had only the Tu Hien inlet that was named Tu Dung. In 1404, the Thuan An inlet was opened so the system had one more inlet. After the opening of the Thuan An inlet in 1404, the Tu Hien inlet has been gradually declined.

Under actions of waves, littoral drift and river flood, the Tu Hien inlet is frequently changing in a morphological cycle since one more inlet of the lagoon has opened. The cycle starts with a breakthrough of the sand barrier at Vinh Hien to open a new inlet in an extreme river flood event. The inlet at this initial phase has its channel in the orientation of NE – SW. Due to the dominant wave induced littoral drift south-eastward, the northern bank of the inlet is accreting and extending as a sand spit in the SE direction. The inlet is then gradually lengthened and changes its direction to SE. When the inlet reaches the rocky coast at Loc Thuy near the cape of Chan May Tay, it declines and is then closed to finish its morphologic cycle.

The last morphological cycle of the Tu Hien inlet lasted for 9 years with its open period of 4 years from 1990 to 1994 and after that it was closed for a period of 5 years from 1994 to 1999 (see Figure 2.2 and Figure I.3 in Appendix I). According to Tran Duc Thanh *et al.* (2000), the morphological cycle of the inlet is becoming shorter than in the past.

The normal dimension of the Tu Hien inlet is 200 m wide and 3m deep. In October 1994, one month before its closure by nature, it had only 50 m wide with a maximum depth of 1 m. After the flood event of November 1999, the inlet is 600 m wide and 4 – 8 m deep. It is currently narrowed by the extension of the updrift barrier south-westward. In March 2001, its width was reduced to about 150 m after 16 months (Tran Duc Thanh *et al.*, 2000).

The Loc Thuy inlet is normally very narrow and shallow causing difficulties for flood evacuation and navigation. After the flood of 1999, it was 200 m wide and 2 – 5 m deep. But the bay end of the inlet has been rapidly accreted and closed.

Inside the Cau Hai lagoon, the flood-tidal delta of the Tu Hien inlet is at the depth of 0.4 – 0.5 m and divided into three parts by narrow 1-m-deep channels. This delta is developing each time when the Tu Hien inlet is opened.

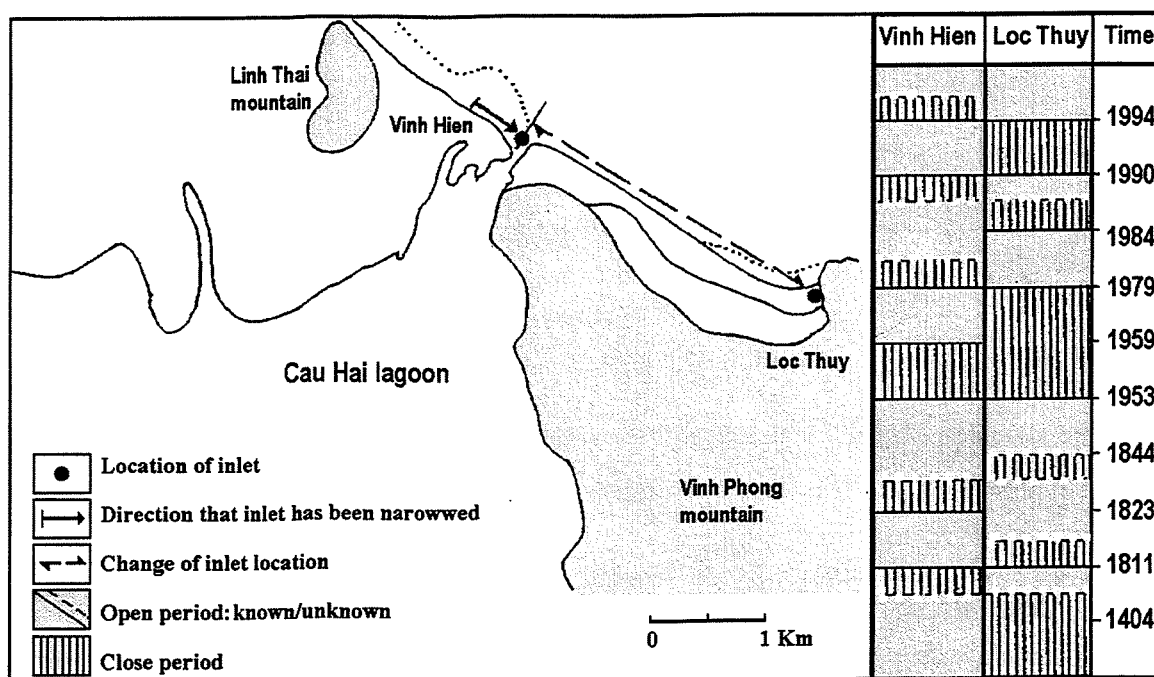


Figure 2.2. Changing location of the Tu Hien inlet (after Nguyen Huu Cu, 1996)

2.2.2.2. The main inlet

The main inlet is the most dynamic and variable one. It has been located at different places from Hoa Duan to Thai Duong Ha and to Thuan An at different moments and has different names of: Thuan An inlet, Hoa Duan inlet, Tan My inlet, “cua Eo”, “cua Nhuyen”, “cua Sut”, “cua Sat”... in Vietnamese (see Figure 2.3 and Figure I.4 in Appendix I).

The main inlet nowadays is the Thuan An inlet. The channel of the inlet is 600 m long orientating NNW – SSE. The Thuan An inlet has a normal width of 350 m and a maximum depth of 11 m inside the lagoon (see Figure I.5 in Appendix I).

In the area of the main inlet, the prevailing long-shore sediment transport is north-westward. This turns the inlet extending to NW and not perpendicular but oblique to the shoreline. The

unbalance of the long-shore sediment transports in the monsoon seasons also makes the ebb-tidal delta asymmetric and becoming a complex structure under wave attacks. This delta is an obstacle for navigation and flood evacuation.

The historical development of the main inlet can be seen in Section 2.3.5.

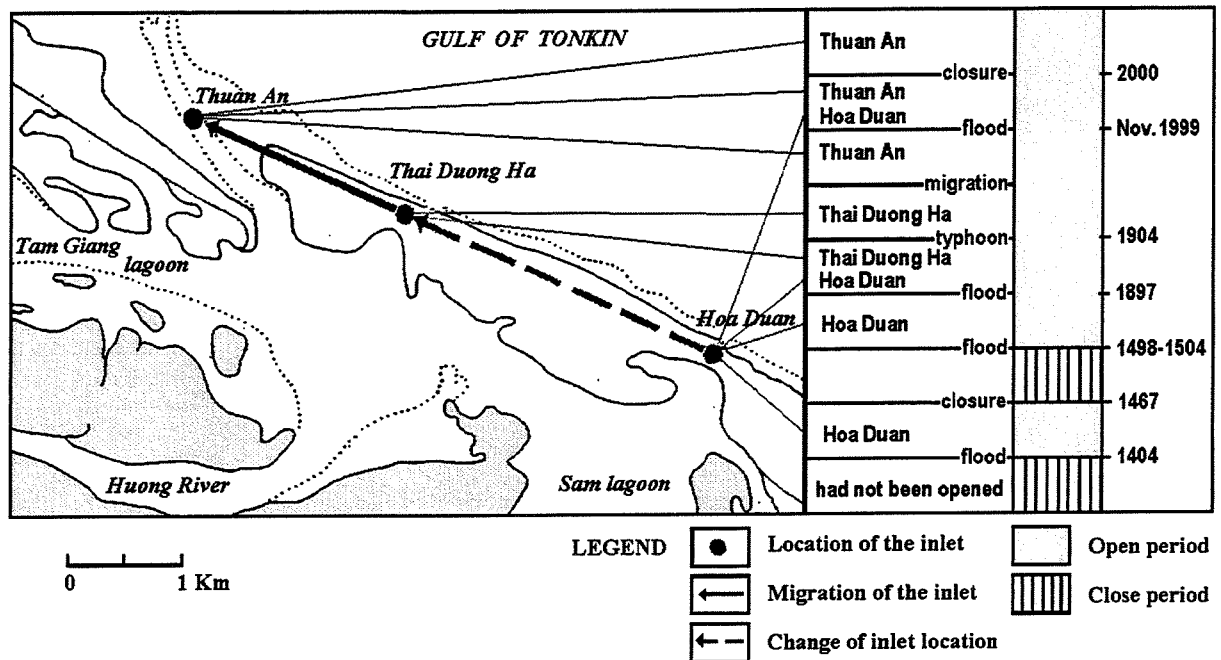


Figure 2.3. Migration and changing location of the main inlet (after Nguyen Huu Cu, 1996)

2.2.3. The sand barriers and the shoreline

2.2.3.1. The sand barriers

The sand barriers include sand dunes, sandbars and beaches extending in the NW-SE direction. The total length of the sand barriers is about 102 km and can be divided into four parts:

- (1) the sand barrier from Cua Viet to Thuan An has a length of 60 km, an average width of 4.5 km, and an average height of less than 10 m. The height of the sand barrier increases from Cua Viet to Thuan An. The maximum height is 32 m at Hai Duong commune.
- (2) the sand barrier from Thuan An to Linh Thai mountain has a length of 37 km, an average width of 2 km, and an average height of 10 m. The height of the sand barrier increases from 2m at Thuan An to 20 m at Phu Dien.
- (3) the sand barrier from Linh Thai to the Tu Hien inlet has a length of 2 km, an average width of 300 m, and an average height of 2.5 m.
- (4) the sand barrier from Tu Hien to Loc Thuy is 3 km long and 2 – 2.5 m high.

The sand barrier from Loc Dien at O Lau river mouth to Thuan An is composed of two sand dune systems overlapping each other. The structure of the sand barrier from Thuan An to Linh Thai is the same.

2.2.3.2. *The shoreline*

The important shoreline of the system is 102 km long in the NW-SE direction. It is limited by the cape of Chan May Tay (granitic bedrock) in the south and the Cua Viet river mouth in the north. The beaches are mainly formed by cross-shore sediment transport due to waves.

The shore is gentle at the depth of 0 – 5m and is quite steep at the depth of 10 – 15 m. The distance of the 10-m depth contour to the shore line is 1.2 – 1.5 km, nearest is 100 m. The shoreline can be divided into two parts:

- The shoreline from Cua Viet to Thuan An is 59 km long and quite homogeneous in orientation and geometry. The beaches are quite stable without serious erosion or accretion. But in the beach of Hai Duong commune (north of Thuan An inlet) erosion rate is 4 to 5 m/year. After the extreme river flood of 1999, the erosion at Hai Duong increased to 8 – 15 m/year.
- The shore from the Thuan An inlet to the cape of Chan May Tay basically orients NW-SE. At a bent of 32 km long from Thuan An to Vinh Xuan, erosion and accretion occur next to each other in a complex process. Along this bent, the beach is narrow and steep with a width of 15 m. Behind the beach is an eroding sand dune with an eroded cliff of 1 – 1.2 m high. Along 3 km of the shoreline near Thuan An and Thai Duong Ha, the shoreline is eroding 15 – 20 m/year during the north-east monsoon season and is accreting 10 – 15 m/year during the south-west monsoon season. The resulting erosion rate every year is approximately 5 m.

2.2.4. **The inland banks**

The total length of the inland banks is 183 km. The portion surrounding Cau Hai lagoon is mainly bedrock. Other parts are Quaternary alluvium from the rivers and sand with marine origin.

2.3. **GOVERNING FACTORS AND SYSTEM CHARACTERISTICS**

2.3.1. **Topographic factor**

The Tam Giang-Cau Hai lagoon collects flow water from a catchment of about 4000 km², equivalent to 4/5 total area of Thua Thien-Hue province. The topography of the drainage basin is very important to the system in term of collecting flood flow.

The topography of the river basin discharging to the Tam Giang-Cau Hai lagoon is complex and can be divided into following areas continuously:

- (1) The high mountain area with heights from 250 – 1770 m and slope of 4.5%.
- (2) The hilly area with its height of 25 – 250 m and slope of 1.1%;
- (3) The delta with its gradual slope of 0.1%.

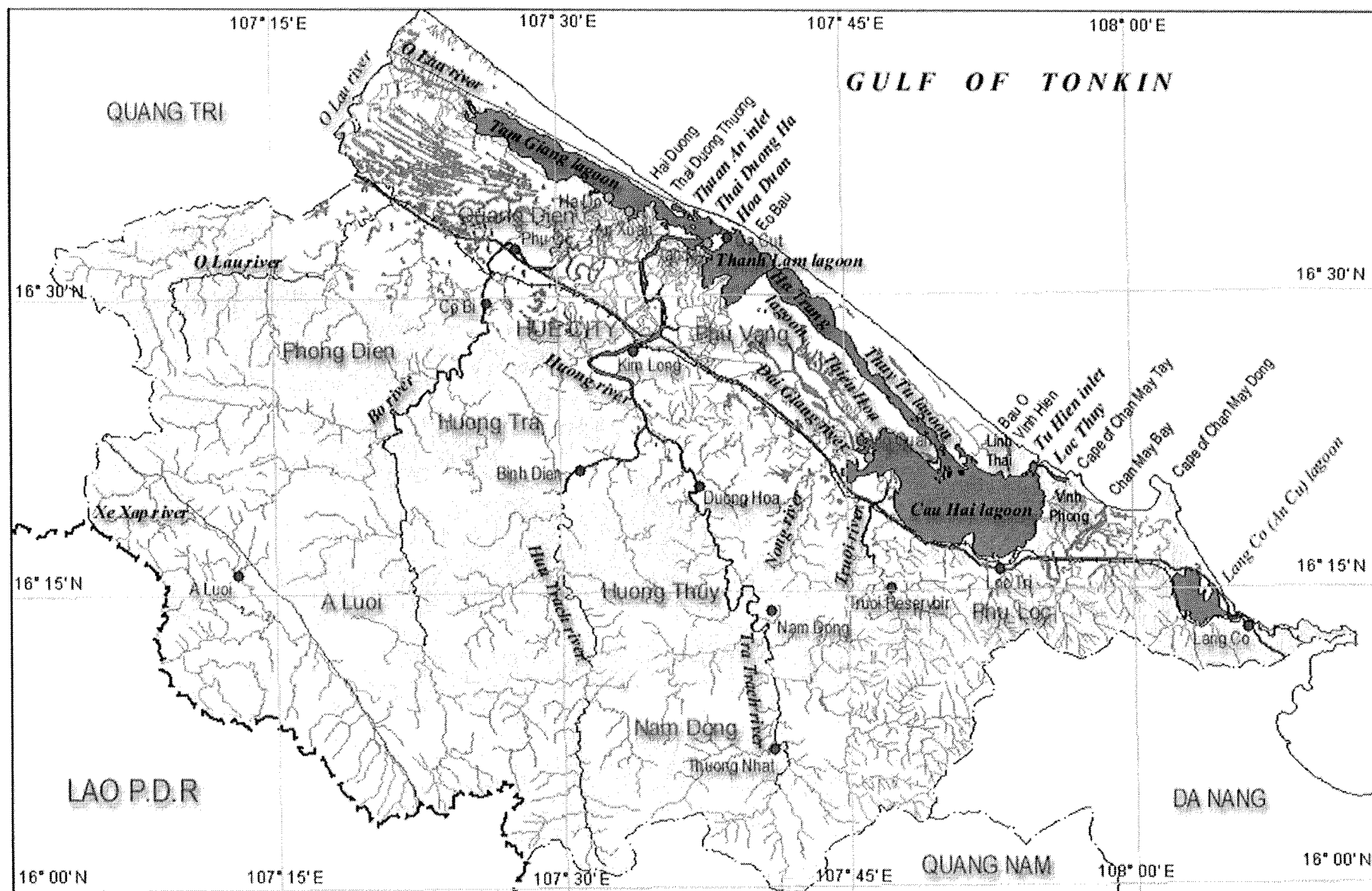


Figure 2.4. The Tam Giang – Cau Hai lagoon and the river network

The high mountainous and hilly areas occupy 80% of the total area of the province with many high and steep cliffs distributed west and south of the Hue delta. These cliffs stop north-east and south-east monsoon winds that are coming from the sea and carrying very high humidity causing very high rainfall in this area. Especially in typhoons, due to very steep slope of the mountain and hilly areas surrounding the Hue delta, water flow is rapidly concentrated and poured to the narrow delta causing flash floods. Because the delta area is small and floodwater is blocked by the sand barriers and small opening inlets, extreme floods always cause serious inundation and damages to this area.

2.3.2. Climatic factors

2.3.2.1. *Temperature, humidity and evaporation*

Thua Thien-Hue province is located in the tropical monsoon area with a not very cold and dry winter and a hot and wet summer.

The mean temperature is about 25°C in the delta (Hue) and 22°C in the mountainous area (A Luoi). The maximum temperature in the delta and mountainous area occur in June or July are 41.3°C and 38.1°C, respectively. The minimum temperature in the delta and mountainous area in January are 8.7°C and 4°C, respectively.

The mean relative humidity in the delta (Hue) and in the mountainous area (A Luoi) are 83% and 87%, respectively. The highest humidity occurs in November at these locations are 89% and 93%, respectively. The lowest humidity occurs in July at these locations are 73% and 79%, respectively.

The evaporation of the area is about 900 mm/year (Hue: 974mm/year, A Luoi: 855mm/year). High monthly evaporation occurs in the dry season with 100 mm/month. High evaporation in the dry season decreases the freshwater budget and increases the lagoon salinity. In the wet season, the monthly evaporation decreases to less than 50 mm/month.

2.3.2.2. *Rainfall*

The rainfall in Thua Thien-Hue province is highest in the country due to effects of monsoons and topographic conditions. Annual rainfall in the mountainous and hilly areas is 3000 – 4000 mm/year. Annual rainfall at Bach Ma is 8000 mm/year (Tran Dinh Hoi *et al.*, 2001). Annual rainfall in the Hue delta is 2500 – 3000 mm/year. The rainfall is very unevenly distributed during a year. A year can be divided into two distinct seasons: the wet season (flood season) from September to December with 70 – 80% of the annual rainfall, and the dry season from January to August with only 20 – 30% of annual rainfall.

The maximum daily rainfall at some locations is from 700 – 1500 mm/day. During typhoons and tropical depressions, very high rainfall may be concentrated in a few days causing very high floods and inundation.

During the flood event of 1999, the maximum rainfall is 1422 mm/day at Kim Long, 1630 mm/day at Truoi, 753 mm/day at A Luoi, 1138 mm/day at Ta Luong. The maximum 2-day rainfall at some locations are Truoi: 2230 mm/48 hrs, other locations are Hue: 1841mm/48 hrs, Phu Oc: 1294 mm/48 hrs, A Luoi: 1120 mm/48 hrs.

2.3.2.3. *Wind conditions*

The area is effected by monsoon systems: the north-east monsoon season in winter and the south-west monsoon season in summer. These monsoons in the area are changed by the topographic condition of the province. In summer, the wind is from the east direction with speed of 1 – 1.5 m/s, where the SW wind is dominant offshore with an occurrence of 56% and speed of 1 – 7 m/s. The occurrence of calm conditions is 30%. In winter, dominant winds are N and NW with an occurrence of 30% and speed of 1.6 – 3 m/s. Strong winds in winter may reach 17 – 18 m/s. Observed data at Thuan An in 1988 indicated NE and N winds were dominant in February with an occurrence of 80% and the occurrence of the NW wind in March was 42%.

Winds have a significant effect on the waves, sediment transport in the shore and surface flow circulation inside the lagoon, contributing to the morphological processes and change of bio-ecological system.

2.3.2.4. *Typhoons, tropical depressions and storm surges*

Vietnam is located in the north-west of the Pacific Ocean, where the highest number of typhoons occur every year. During the last 100 years, 493 typhoons and tropical depressions have approached the coastal provinces of Vietnam, 87 of these (18%) have hit Thua Thien-Hue province. In average, there are 0.87 typhoons hitting the province every year. The occurrences of typhoons are from June to November and highest in September and October (64%).

Typhoons are normally accompanied with violent winds, gust bumps, high rainfall and storm surges. The maximum wind speed during a typhoon is 15 – 20 m/s in average. Highest observed wind speed is 38 m/s.

During the last 30 years, 50% of typhoons were accompanied with storm surges of over 1 m, 30% of typhoons causing storm surges of over 1.5 m, and a few typhoons have coupled with a storm surge exceeding 2.5m. On 15 October 1985, the typhoon Cecil with a wind speed of level 12 hit the area causing storm surge of 2.25 m (VIWRR, 2000; Le Bac Huynh *et al.*, 1999).

The high floods upstream and high storm surges in the sea caused by typhoons destroy sea dykes, breach river dykes and cause flooding and inundation of the coastal lowland areas. Typhoons and tropical depressions are natural disasters causing losses of human life, destroying infrastructure and their properties such as house, fishing boat, crops. Typhoons, floods and storm surges cause erosion of the sand barriers, change morphology of the lagoon and inlets.

2.3.3. **River system and river flow to the lagoon**

Almost all of the rivers in the area have their origin inside the province's interior and discharge into the Tam Giang-Cau Hai lagoon, except the Xe Xap River. These rivers are the O Lau River, the Dai Giang River, the Cau Hai River, the Nong River, the Truoi River and the largest river – the Huong River with its tributaries of Huu Trach, Ta Trach and Bo rivers.

Total catchment of the rivers is about 4000 km². The Huong River with its tributaries occupy 75% of this with 3000 km². Other river basins are the O Lau River with 300 km², the Dai Giang River with 180 km², the Nong River with 66 km² and the Truoi River with 50 km².

The rivers commonly originate at an elevation of 200 m and flow on the steep slope 20 – 29%. Therefore these rivers are quite straight and steep. This is an auspicious condition for collecting of rainfall water to create severe floods and inundation.

The distribution of the river flows is very uneven during a year. The flow is concentrated in the flood season from September to December with 70% or more of the annual flow.

In the dry season from January to August, monthly river flow is more than 10 l/s/km², is higher than other areas in the Central Coastal Area of Vietnam.

In the flood season from September to December, high rainfalls on steep surfaces of the basins usually create floods on the rivers. The floods occur nearly immediately after starting of rains with high and rapidly changing flow discharges. During the floods, the water levels in the rivers are highly risen causing inundation in the lowland and coastal area of the delta. Effects of tides on water levels in the rivers are dimmed by the floods. Small openings of the inlets and the obstruction of the sand barriers to the flood evacuation contribute to the inundation in the area more serious. High flood discharges and water levels can cause breakthrough of the sand barriers at weak points, and may change the locations of the inlets.

Flow discharges and water levels of the rivers are observed by Vietnam Hydro-Meteorological Services (HMS) at four gauging stations of Thuong Nhat (Ta Trach River), Binh Dien (Huu Trach River), Co Bi (Bo River) and Nguyet Bieu (Huong River). Observations at Nguyet Bieu were made only from 1963 to 1973. Three other stations started observations from 1979 and are still in operation. At Kim Long on the Huong River and Phu Oc on the Bo River, only water levels are observed. Other locations such as Duong Hoa on the Ta Trach River, Nguyet Bieu, Tan My and Cong Chanh on the Huong River, Ca Cut in the Tam Giang lagoon, Cong Quan on the Dai Giang River and Truoi River, flows were observed in only very short periods. The flow data of the rivers at some gauging stations are listed in Table 2.1.

Table 2.1. The flow characteristics of the rivers (after Ngo Dinh Tuan *et al.*, 2001)

Station	River	Basin area F (km ²)	Annual flow			Minimum flow			
			Q ₀ (m ³ /s)	M ₀ (l/s/km ²)	W ₀ (10 ⁶ m ³)	Q _{min} (m ³ /s)	M _{min} (l/s/km ²)	Q _{month} (m ³ /s)	M _{month} (l/s/km ²)
Thuong Nhat	Ta Trach	208	15.8	76	500	1.46	7	2.19	10.5
Duong Hoa	Ta Trach	720	58.8	82	1856				
Binh Dien	Huu Trach	570	42.1	74	1330	2.16	3.8	6.50	11.4
Tuan	Huu Trach	800				5.80	7.25	9.60	12.0
Co Bi	Bo	760	61.2	81	1930				
Truoi Reservoir	Truoi	75.3	11.8	157	372				

In the rainy season, flows in the inlets are mainly from the lagoon to the sea (Nguyen Tuan Anh *et al.*, 1999).

2.3.4. Oceanographic factors

The coast of Thua Thien Hue province is exposed directly to the open sea in the relatively shallow area of the Gulf of Tonkin. The length of Thua Thien-Hue coast is 120 km aligned in the NW-SE direction.

2.3.4.1. Tides and tidal currents

Along the Thua Thien-Hue coast, the variation of the tides are complicated. In the northern and southern areas of the coast, the tidal regimes are mixed with dominant semi-diurnal. In the area of the Thuan An inlet, the tidal regime is fully semi-diurnal. The coast is located in the Northern Hemisphere so the flood tidal propagation direction is south-eastward. The tidal range is about 0.6 – 1.2 m in the NW part of the coast and reduces southward to the Thuan An inlet. The tidal range at Thuan An is smallest along the coast with the value of 0.3 – 0.6 m. It is the micro-tidal regime in the hydro-dynamical classification according to Hayes (1979) (see De Vriend *et al.*, 2000; USACE, 1989). From the Thuan An inlet, the tidal range increase southward with a value of 0.55 – 1.0 m at the Tu Hien inlet. The observed data of the Management Board of the Huong River Projects (Nguyen Tuan Anh *et al.*, 1999) at the Thuan An inlet indicates the highest HW is +1.5m and the lowest LW is -0.7m.

Tidal currents in the area of Thuan An are 0.25 – 0.30 m/s at the water depth of 10 – 15 m. Tidal currents decrease seaward and decrease with the increase of the water depth.

2.3.4.2. Waves and longshore currents

Waves are the dominant driving force in the Thua Thien-Hue coast. The wave conditions are directly influenced by the wind conditions that are distinguished of two main monsoon seasons: the north-east monsoon season in winter (winter monsoon) and the south-west monsoon season in summer (summer monsoon).

In the winter monsoon season from September to March, dominant waves are E and NE near-shore and N offshore. Observation in February 1998 shows that the occurrence of NE waves at Thuan An are 99% with the fluctuation of wave heights are from 0.25 up to 3 m (Nguyen Tuan Anh *et al.*, 1999).

In the summer monsoon season, dominant waves are SW and SE offshore and SE near-shore. From observed data in 1998, the occurrence of E waves at Thuan An is 93% with wave heights from 0.2 – 1 m (Nguyen Tuan Anh *et al.*, 1999).

During severe conditions of a violent typhoon, the wave height can rise to 7 - 8 m. The data of wave period is not available.

Wave induced longshore currents are the main factor of the sediment transports in the surf zone. The directions of the longshore currents are quite stable in a monsoon season. The direction of the longshore currents is north-westward in summer and south-eastward in winter. The velocity of the longshore currents is from 0.3 – 1 m/s and highest in winter during north-east monsoon season.

2.3.5. The characteristics of the lagoon water body

2.3.5.1. Salinity and salt intrusion

Water inside the lagoon is brackish. The salinity is varying in space and time and is sensitive to the tidal changes (see Figure I.6 in Appendix I). In the flood season, the salinity of the lagoon decreases to 0 - 6‰. Stratification is clearly observed in the Tam Giang and Cau Hai lagoons. In the dry season, the water depth in the Tam Giang lagoon is only 1.7 m, but the difference of salinity between the upper layer and the lower layer of the water column can reach 13.5‰ in the lagoon and 12.2‰ in the Huong River mouth area. Normally this value is 2 - 6‰. In the flood season, the lagoon salinity decreases and the stratification is reduced. The highest difference of salinity occurs in the Thuan An inlet with a value of 8.4‰ (Tran Dinh Hoi *et al.*, 2001).

The maximum salt intrusion length of about 30 km has been observed on the Huong river. Salt intrusion has a reverse effect to agriculture in the lower areas of the Huong River and O Lau River and has a significant role in the lagoon ecosystem. The total cultivated area that is effected by salt intrusion is 2000 – 2500 ha (Tran Dinh Hoi *et al.*, 2001).

2.3.5.2. Water temperature

Water temperature of the lagoon is different between the upper and lower layers. In summer, water temperature of the upper layer is 1 – 3°C higher than the lower layer. In winter, the situation is in contrary.

2.4. PAST STUDIES ON THE TAM GIANG-CAU HAI LAGOON SYSTEM

2.4.1. Historical development of the inlets

For many centuries, the Tam Giang-Cau Hai lagoon and tidal inlet system has had an important role in navigation, fishery, aquaculture, agriculture, defence and tourism of Thua Thien-Hue province and the Central Coastal Area. For many centuries, feudal dynasties and local people have been trying to control the system. According to the historical records, the development of the inlets and they attempts can be listed as follows (Tran Dinh Hoi *et al.*, 2001; Nguyen Quang Trung Tien *et al.*, 2001; Tran Duc Thanh *et al.*, 1996)

- Around 1500 AD, there was an opening at Hoa Duan to form the second inlet at the location of about 4 km in the south of the present Thuan An inlet.
- After the open of the Thuan An inlet in 1404, the inlet was closed by the decision of the king Han Thuong of the Ho dynasty but it was opened again by floods after that.
- In 1467, the king Thanh Tong of the Le dynasty ordered to close the Hoa Duan inlet.
- In 1498-1504, the Hoa Duan inlet was opened again.
- In 1823, the king Minh Mang of the Nguyen dynasty ordered to dredge the Tu Hien inlet.

- In 1868 and in 1880s, the Nguyen dynasty ordered to close the Hoa Duan inlet and the Huong River mouth to defend against the French battle ships. On 20 August 1883 these closure dams were damage by the French army to get a opening for navigation of battle ships.
- On 15 October 1897, a new inlet was formed at Thuan An and since then, the Hoa Duan inlet began to decline.
- On 11 September 1904, the Hoa Duan inlet was completely closed during a severe typhoon.
- In 1920s, the Thua Thien Provincial Department of Irrigation and Drainage did many studies on building a closure dam at the Thuan An inlet to prevent salt intrusion in lowland cultivated areas of Phong Dien, Quang Dien, Huong Tra and Phu Vang districts.
- In 1928, the Vallette project started building a closure dam to close the Thuan An inlet.
- In October 1928, the closure dam was damaged in the middle part with a length of 120 m and a depth of 7m after a big flood. But the Vallette project was continued under the execution of French engineers Perrier and De Rouville.
- In 1930, the construction of a partly submerged dam, 2000 meters long; top elevation at MSL+2.0 m in the Thuan An inlet was completed by the French. The main purpose of this dam was probably to reduce salt intrusion inside the lagoon and paddy field downstream of the Huong River.
- A sea dyke with a length of more than 17 km was built in the same year to control salt intrusion.
- After that, there was a significant damage of the dam caused by flood discharges of the Huong river. The top elevation of the dam was reduced from MSL+2.0 m to MSL+0.0 m in the middle part.
- In 1937, Debeau Cham and Déplangue recommended to develop a water resources project in the Huong river basin for the purposes of irrigation and hydropower. The Thuan An closure dam was proposed to be removed. But this project has not been implemented.
- In 1953, the dam was partly damaged during the flood season. On 23 September 1953, a big flood almost destroyed the dam with a damaged length of 300 m and to the level of MSL-18 m. Also the sea dyke system was seriously damaged by the typhoons. Salt intrusion then penetrated deeply into the interior of the Huong river delta, effected on cultivation in the surrounding area of the lagoon.
- In 1960s, US Army invested a lot of dredging in the Thuan An inlet area to turn this area into a small military port.
- In 1961, SOGREAH had an idea of a big project to build a barrage at the Huong river mouth for irrigation and salt intrusion control. But the project was not implemented and the barrage could not be built due to the limitation of the construction technology did not allow to construct such kind of dam at that time.

- In 1965, the remaining part of the Thuan An closure dam was removed by US Army.
- At the same time, a project to develop Tan My port for US Army including access channel in the Thuan An inlet was implemented by the America. A scale hydraulic model of the inlet was built to study hydraulic and morphological conditions of the inlet and access channel (see Lee, 1970).
- In 1969, a steel jetty of 200 m long was constructed just 150m south of the inlet in order to create a harbour facility for army vessel and prevent siltation in the access channel of the Thuan An inlet. This jetty lasted until the years of 1979, 1980.
- On 3 November 1999, during an extreme flood, the sand barrier at Hoa Duan strait, the narrowest point of the sand spits, has been broken. In the initial state of broken, the gap at Hoa Duan had a width of 620m and a depth of 7 m. After the flood, the Thuan An inlet was widened to 700 m with its area of 6200 m². The depths of this inlet were 13 – 15m maximum but decreasing seaward.
- In July 2000, the gap at Hoa Duan was closed with a closure dam of sandbags and armoured with concrete blocks. The main purpose of the closure is to rehabilitate a major provincial transport road from Hue and Thuan An town to the villages in the south of Hoa Duan. One week after the completion of the closure, due to a high river flood on the Huong river, which caused by a tropical depression, the closure dam was partly broken and the gap was opened again.
- In September 2000, once again the gap at Hoa Duan was closed.
- The Tu Hien inlet was also paid many interests on its open or close.

2.4.2. Previous studies on the area

Before 1975, the researches of the French and the America on the system only focused on either salt intrusion control or shoaling of the access channel in the Thuan An inlet. These researches were for either agricultural or military/defence purposes and did not take into account other aspects.

After 1975, more attentions have been paid to this area by the Vietnamese Government, by the local authorities and by many scientists in the country or overseas. Researches paid to the Tam Giang-Cau Hai lagoon system can be listed as follows:

- In 1995, the National Research Project KT-03-11 studied on the reasonable utilisation of the coastal ecosystems in Central Vietnam. As a result of the project, a scientific seminar on the Tam Giang lagoon was held in November 1994 to exchange point of views of scientists, planners and managers on the nature and current utilisation of the lagoon and a plan for integrated studies and developing regional economy.
- Until 1995, it can be concluded that there was only one mathematical model of the Tam Giang-Cau Hai lagoon as a system. This is a 2D wind driven model with the only forcing function introduced is wind. Introduction of river discharge and water level variation due to tides was mentioned, but none of these effects has been incorporated in the working version of this model. The density problem has not been taken into account in the model

too. Calculations carried out concentrated on steady state cases on a rectangular grid of 500m×500m. The obtained results of the model were assessed and have not been acceptable (see VVA Project, 1996).

- In 1996, the National Research Project KT-DL-95-03 focused on the study on the reasonable utilisation the potential of the Tam Giang lagoon. The project was a comprehensive study on characteristics of hydrometeorology, geology, geomorphology, sedimentation, environment and water quality, lagoon biology, situation and development of fishery in relation to aquaculture in the lagoon. The result of the project is considered as a good reference for further studies (Tran Dinh Hoi *et al.*, 2001).
- In 1997, a system of 5 groins was constructed in the southern coastline of Eo Bau (near the Hoa Duan inlet when it was not open) by the local authorities.
- In 1999, a research project on the solution for siltation of the Thuan An inlet and protection of the coastline from Thuan An inlet to Eo Bau was implemented by the Vietnam Institute for Water Resources Research (VIWRR). But the result of the study has not been applied due to the extreme flood in November 1999.
- In July 2000, the closure of the Hoa Duan gap was done by the Ministry of Transportation and it is now being under discussion.

All the previous studies are considered partial and passive. There is no project that can be seen as an integrated project for the sustainable development of the area (Tran Dinh Hoi *et al.*, 2001).

In July 2001, a research project was done on the overall solution for the area of coastal inlets Thuan An-Tu Hien and the Tam Giang - Cau Hai lagoon. A 1D hydraulic numerical model was used to simulate flood flows in the river network. A 2D hydrodynamic model with a rectangular grid was used to study only effects of different cases of tidal inlet openings on flood evacuation (see Ngo Dinh Tuan *et al.*, 2001; Tran Dinh Hoi *et al.*, 2001). Salt intrusion, sediment transport, wave and morphology processes of the lagoon and tidal inlets system have not been study in this project. Reason for this limitation is the tool for solving all the problems of the lagoon together is not available in Vietnam.

2.5. CONCLUSIONS

The Tam Giang-Cau Hai lagoon system is basically formed in the late Holocene. The system has encountered through the initial and young stages and is being in its development stage under complicated effects by waves, tides and river flows in combination and interaction. The lagoons are now relatively separated and are different in their characteristics.

During the development process of the system, waves, tides, sediment transport and river flows are the important governing factors directly effect to the system in the basis of topographic, geologic and climatic features. Human activities also contribute to the development of the system.

For many centuries, feudal dynasties and local people have been trying to control the system but they were unsuccessful. Recent studies have not taken into consideration effects of relevant hydrographic, hydrodynamic and geomorphologic processes in combination.

The proper solution for the issued problems of the system must take into account all important hydrographic and hydrodynamic aspects of such a tides, waves, sediment transport and morphology of the system.

Chapter 3. OVERVIEW ON THE STUDIES ON LAGOONS AND COASTAL INLETS

3.1. LAGOON AND TIDAL INLET GEOMORPHOLOGY AND GEOLOGY

3.1.1. Coastal lagoon

The Tam Giang-Cau Hai lagoon is a coastal partly closed lagoon in a low-latitude humid region. According to Phleger (1981), coastal lagoon is a brackish or saline basin entrapped behind coastal barriers and connected with the ocean by one or more inlets. Coastal lagoons and tidal inlets are prevalent morphologic features of the lowland coasts all around the world (USACE, 1989; De Vriend *et al.*, 2000).

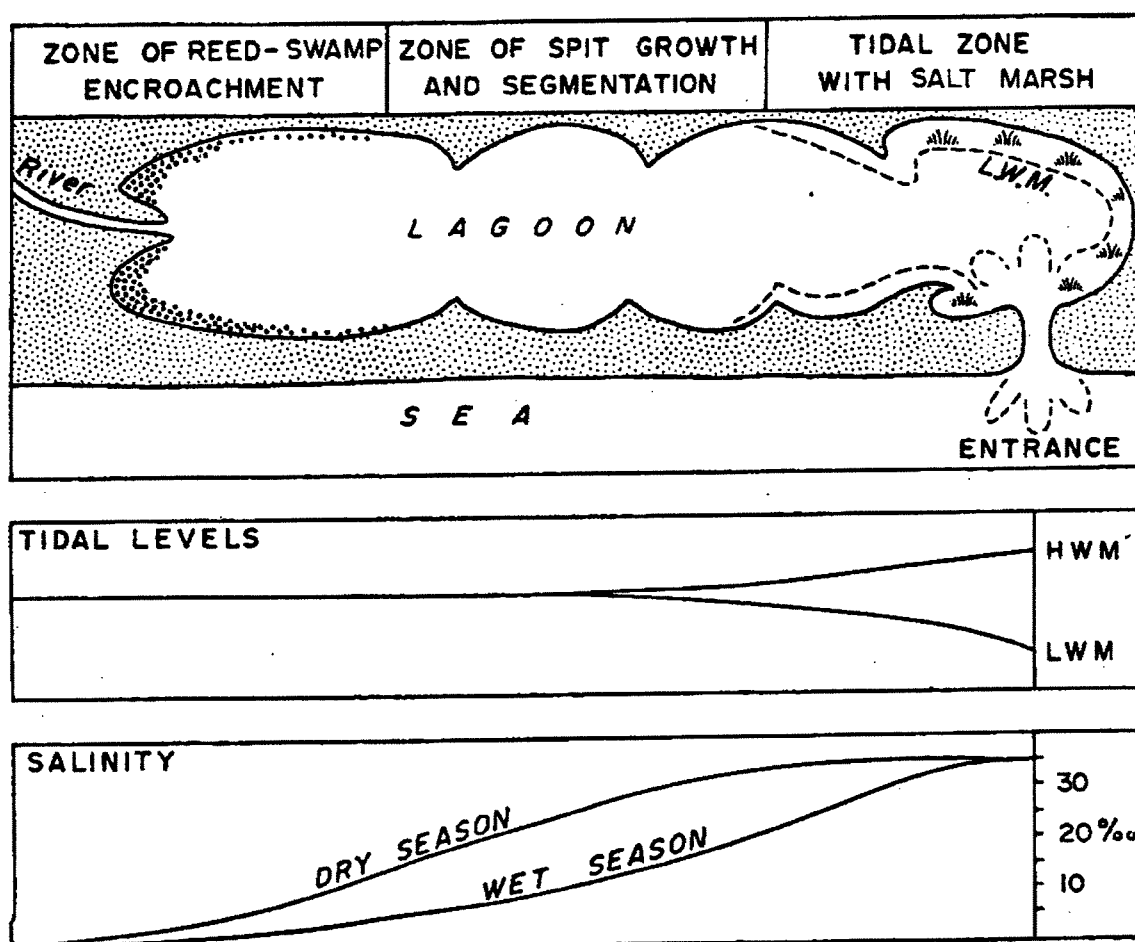


Figure 3.1. Diagram of a coastal lagoon, showing variations in tidal levels and seasonal salinity conditions (Bird, 1968)

According to Bird (1968), lagoons have formed where inlets or embayments produced or revived by the Holocene marine submergence have become enclosed by depositional barriers of sand or shingle. They show a wide variety of geomorphological and ecological features. The essential characteristics of lagoons can be summarised in Figure 3.1. There are often three zones: a freshwater zone close to the mouths of rivers, a saltwater tidal zone close to the entrance, and an intervening transitional zone of brackish (moderately saline) but relatively

tideless water. The proportions of each zone may vary from one system to another. The extent of each zone depends largely on the proportion of freshwater inflow to the lagoon system and on the nature and dimensions of the entrance from the sea.

The initial form of a coastal lagoon depends on the shape of the inlet or embayment enclosed and the configuration of the barriers that enclose it.

Detailed studies of the geomorphology and ecology of coastal lagoons include Webb (1958), Stevenson and Emery (1958), Fisk (1958), Zenkovitch (1959). In terms of the geological time scale, coastal lagoons are ephemeral features, likely to be replaced by depositional plains or reopened as coastal embayments, depending on the subsequent evolution of the coastal region in which they have developed (Bird, 1968).

3.1.2. Tidal inlet

A tidal inlet is a relatively small-scale waterway that connects an inland body of water such as a lagoon, bay, or estuary with a larger tidal body as an ocean and serves as a conduit for the exchange of water during the tidal cycle between these bodies (USACE, 1989; De Vriend *et al.*, 2000). Many tidal inlets provide the primary navigation link between the ocean and inland waterways, harbours, ports.

Tidal inlets serve as extremely important conduits for the exchange of water and sediments between bays, lagoons, or estuaries and the continental shelf. They play an important role in coastal processes, sedimentation and erosion. Because tidal inlets interrupt the uniformity and continuity of coastal processes and sediment transport, tidal inlets exert a tremendous influence on shoreline erosion/deposition trends, sediment budgets, and migration history. Many tidal inlets are either ephemeral in nature or are associated with rapid large-scale morphologic changes. Thus, the behaviour of inlets can have extremely significant environmental, social, and economic impacts (USACE, 1989; De Vriend *et al.*, 2000).

3.1.2.1. Tidal inlet morphologic features

Geomorphology of an tidal inlet varying depends on the hydrographic and hydrodynamic regime, specifically, tidal range, tidal prism, wave energy, and sediment transport. The balance and interaction between these parameters dictate the relative size, distribution, and abundance of inlet-affiliated morphologic features. The principal morphologic units associated with tidal inlets are tidal deltas and inlet channels (USACE, 1989).

3.1.2.1.1 Tidal deltas

Sand deposits in the interior shoal and the outer shoal of a tidal inlet are defined as tidal deltas. Hayes (1969, 1980) proposed the following terminology and definitions for tidal deltas:

- Ebb-tidal delta: sediment accumulation seaward of a tidal inlet, deposited primarily by ebb-tidal currents and modified by waves
- Flood-tidal delta - sediment accumulation formed on the landward side of an inlet by flood-tidal currents.

3.1.2.1.2 Inlet channel sections

According to Bruun (1978), there are normally four different sections of the inlet channel must be analysed separately:

- The gorge channel - the section with minimum cross sectional area where primary tidal flows occur and usually with relatively little wave action;
- The bay section with its shoals and flood channels;
- The ocean section which may include shoals or bars and one or more ebb channels. Wave action plays an important role in the development of the ocean section.
- The intermediate section is the section between the ocean section and the gorge where currents and wave combine.

3.1.2.2. Tidal inlet classification

There are several classification schemes for tidal inlets such as geological, morphological and hydrographical classification schemes. All of these underscore the inherent relationship between tidal inlets and the associated barrier island shoreline. The hydrographical classification developed by Hayes (1979) is currently the most popular with sedimentologists and coastal geomorphologists and has been accepted as a standard (USACE, 1989).

The hydrographical classification of Hayes based on the main driving forces in hydrodynamics of the coast are waves and tides. Both of these are independent of the inlet system configuration. The wave conditions are generated seaward of the inlet so can be considered independent with it. The tidal range outside an inlet depends primarily on the ocean tides and their interaction with the continental shelf (De Vriend *et al.*, 2000).

Wave action is generally considered to act as a bulldozer on the tidal inlet morphology (Hageman, 1969). Waves move sediment onshore and limit the development area of the ebb tidal delta. The wave climate is generally characterized by the yearly averaged value of significant wave height H_s as in Table 3.1 (De Vriend *et al.*, 2000):

Table 3.1. The classification of wave climate

Class	Mean significant wave height H_s (m)
Low wave energy	< 0.6
Medium wave energy	$0.6 \div 1.5$
High wave energy	> 1.5

Hayes (1975) identified consistent morphologic trends for each of the three classes of microtidal, mesotidal, and macrotidal coasts delineated by Davies (1964) (see USACE, 1989) based on regional observations of coastlines from around the world. By a combination of mean wave height and mean tidal range, Hayes (1979) modified the Davies classification to

give a hydrographical classification of coast and tidal inlets as indicated in Table 3.2 and Figure 3.2.

Table 3.2. The hydrographical classification of coast and tidal inlets and shoreline morphologic characteristics

Class	Tidal range (m)	Shoreline morphologic characteristics – Medium wave energy ($H_s = 0.6-1.5$ m)
Microtidal	< 1	- Long, linear barrier islands. - Frequent storm washover terraces. - Infrequent tidal inlets. - Poorly developed ebb-tidal deltas. - Well-developed flood-tidal deltas.
Low-mesotidal	1 - 2	- Short, stunted (drumstick) barrier islands. - Numerous tidal inlets. - Well-developed ebb-tidal deltas. - Poorly developed or absent flood-tidal deltas. - Downdrift offset configuration related to wave refraction around large ebb-tidal deltas.
High-mesotidal	2 - 3.5	
Low-macrotidal	3.5 - 5	- Barrier islands absent. - Well-developed tidal flats and salt marshes. - Depositional features in the form of linear sand shoals or tidal current ridges. - Funnel-shaped embayments.
Macrotidal	> 5	

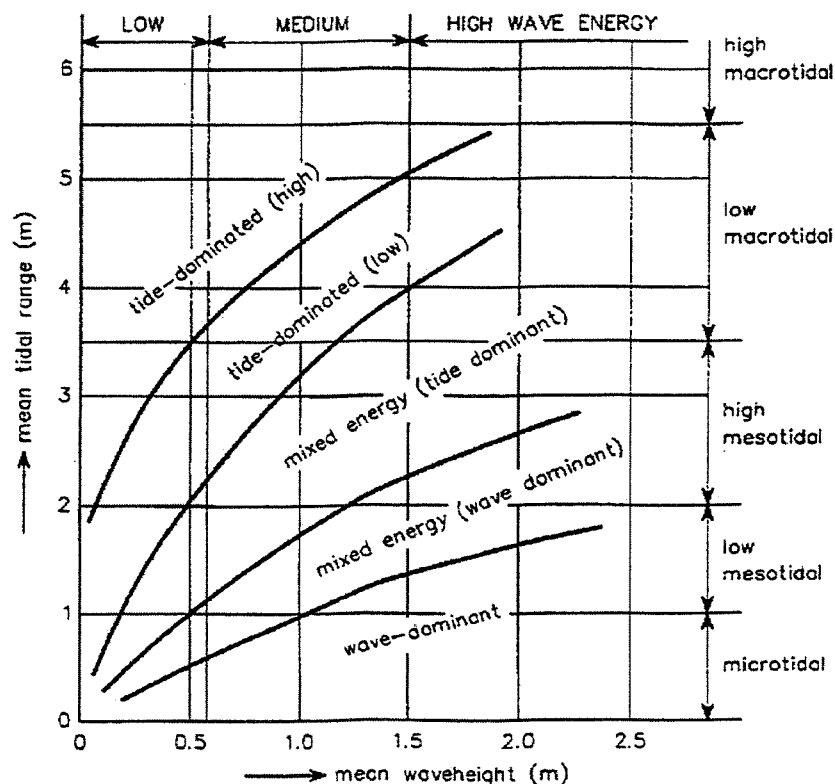


Figure 3.2. The hydrographical classification of coast and tidal inlets

As can be seen in Figure 3.2, because the relative effect of waves and tides is important Hayes distinguishes the tidal inlet into five regions with respect to tidal/wave dominance:

Region 1: wave dominant

Region 2: mixed energy – wave dominant

Region 3: mixed energy – tide dominant

Region 4: tide dominant – low

Region 5: tide dominant – high

In case of the Tam Giang-Cau Hai inlets, as mentioned in Chapter 3, the tidal range outside the inlets is from 0.3 – 1.0 m and the yearly averaged significant wave height H_S is about 1.4 m, they can be classified as the microtidal wave-dominated inlets.

3.2. HYDRODYNAMIC ANALYSIS OF TIDAL INLETS

Inlets have been the focus of intense study by hydraulic engineers for many years (Watt 1905; Brown 1928; O'Brien 1931; Escoffier 1940, 1977; Bruun and Gerritsen 1960; Keulegan 1967; King 1974; Ozsoy 1977; Bruun 1978; van de Kreeke 1988). Hydraulic characteristics of interest to the practising engineer consist of temporal and spatial variations of currents and water level in the inlet channel and vicinity.

3.2.1. Governing equations

Flow in an inlet can be expressed by the system of one-dimensional partial differential equations for long waves in shallow water as follows (Dronkers, 1964; Abbott, 1979)

$$\begin{cases} B \frac{\partial Z}{\partial t} + \frac{\partial Q}{\partial x} = 0 \\ \frac{\partial Q}{\partial t} + gA \frac{\partial Z}{\partial x} + \frac{\partial(\alpha QV)}{\partial x} + g \frac{|Q|Q}{C^2 AR} = b\gamma w^2 \cos(\Phi - \phi) \end{cases} \quad (3.1)$$

where

Z	water level with respect to the reference level (m)
Q	flow discharge (m ³ /s)
V	cross-section averaged flow velocity (m/s)
A	cross-sectional flow area (m ²)
B	cross-sectional storage width (m)
b	cross-sectional flow width (m)
R	hydraulic radius (m)
h_c	mean flow depth (m)
C	Chézy coefficient (m ^{0.5} /s)
n	Manning's roughness coefficient
α	correction factor for non-uniform distribution of the flow velocity in the advection term
γ	wind conversion coefficient
Φ	wind direction (degrees)

- ϕ direction of channel axis measured clockwise from the north (degrees)
 g acceleration due to gravity (m/s^2)
 x distance measured along channel axis (m)
 t time variable (sec.)

The solution of the system of equations 3.1 can be obtained by either analytical methods with simplifying assumptions or numerical methods with discretisation.

3.2.2. Analytical methods

Depending on the degree of accuracy of the type of information needed, several predictive approaches are available. Although only approximate, relatively simple analytical procedures are commonly employed and yield quick answers.

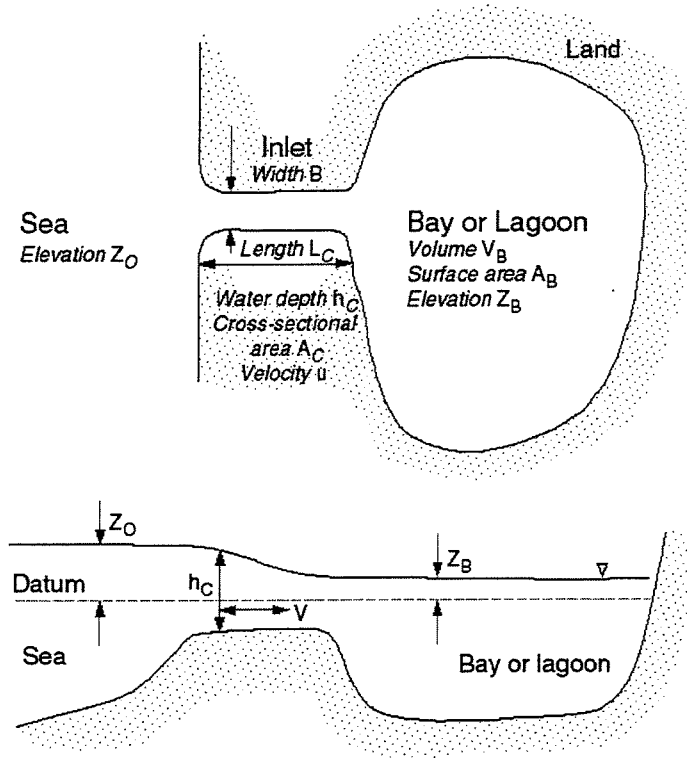


Figure 3.3. Inlet-bay system (after Seelig, Harris, and Herchenroder, 1977)

Consider an idealised inlet system as in Figure 3.3 consists of a relatively short and narrow, but hydraulically wide, channel. The sea tide represents the boundary condition, or forcing function, at one end of the channel and the bay or lagoon at the other. Wind force is not taken into account $w = 0$, $R \approx h_C$, $C = \frac{1}{R} n^{1/6} \approx \frac{1}{h_C} n^{1/6}$, and $\alpha \approx 1$. The momentum equation of the system of equations 3.1 can be rewritten as

$$\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} + g \frac{\partial Z}{\partial x} + g \frac{n^2 |V| V}{h_C^3} = 0 \quad (3.2)$$

Many researchers (Brown, 1928; Escoffier, 1940, 1975; Keulegan, 1951, 1967; Baines, 1958; van de Kreeke, 1967; Mota Oliveira, 1970; Shemdin and Forney, 1970; Dean, 1971; Huval and Wintergerst, 1973; King, 1974; Goodwin, 1974; Freeman, Hamblin and Murty, 1974; King and Shemdin, 1975; Mehta and Ozsoy, 1978; Walton and Escoffier, 1981) tried to simplify the equation 3.2 to get the analytical solutions. Simplifying assumptions associated with Equation 3.2 may include: bay and ocean current velocities are negligible compared to those in the channel; tidal amplitude is small compared to mean depth; change in water volume in the channel due to tidal variation is negligible compared to mean volume in the channel; the tide propagates rapidly through the bay (i.e. the bay is relatively small and deep) so that spatial gradients in the water surface at any instant may be ignored; the bay surface area and freshwater discharge are independent of time; the ocean tide is considered to be sinusoidal; the freshwater inflow and the inertia term have been ignored ... Although these analytical solutions are of limited accuracy, they provide insight into the response of inlet-bay systems to tidal forcing and may be used as an order of magnitude check on more rigorous numerical solutions.

Among the analytical solutions, Keulegan's (1967) solutions are attractive because of their relative simplicity and are frequently incorporated in the derivation of inlet stability criteria. Assumptions include: a) sinusoidal ocean tide, b) vertical inlet and bank walls, so that the water surface area remains constant, c) small tidal range compared to water depth, d) small time variation of water volume in the channel compared to mean channel volume, e) horizontal water surface of the bay, f) mean water level in the bay equal to that of the ocean, g) negligible flow acceleration in the channel, and h) no freshwater discharge. The head difference, therefore, is due to bed frictional dissipation, and entrance and exit losses and the momentum equation can then be solved for the channel current velocity and bay tide.

Keulegan's results include the phase lag between bay and ocean tides and dimensionless values of bay amplitude. Both of these can be related to the dimensionless parameter K introduced by Keulegan as an expression for the hydraulic and geometric characteristics of an inlet and referred to as the coefficient of filling or repletion (Equation 3.3).

$$K = \frac{1}{\sigma u_o} \frac{A_c}{A_b} \left(\frac{2ga_o}{F} \right)^{\frac{1}{2}} \quad (3.3)$$

where

- K repletion coefficient
- A_c channel cross-sectional flow area (m^2)
- A_b surface area of the bay or lagoon (m^2)
- a_o tidal amplitude in the ocean (m)
- σ Tidal wave frequency (radians/sec)
- F head loss coefficient represents the effect of all influence restricting flow and is referred as the overall impedance of the inlet (O'Brien and Clark, 1974)

Keulegan also presented the relationship between K and dimensionless maximum velocity in the inlet V'_{max} . The maximum velocity V'_{max} through a specific inlet is given by

$$V'_{max} = V'_{max} \sigma a_o \frac{A_b}{A_c} \quad (3.4)$$

In the case of a single inlet-bay system with sinusoidal ocean tide, the tidal prism can be closely approximated by

$$P = \frac{2Q_{\max}}{\sigma C_K} \quad (3.5)$$

where $Q_{\max} = V_{\max} A_C$ is the maximum discharge and C_K is a parameter that varies with the repletion coefficient K . C_K essentially accounts for the nonlinearity in the variation of discharge Q with time as a result of the quadratic head loss. At $K=1$, $C_K = 0.811$ and at $K=4$, $C_K = 0.999$ (Keulegan 1967). For simple calculations, an average value of 0.86 has been recommended by Keulegan and Hall (1950) and O'Brien and Clark (1974).

3.2.3. Numerical models

Despite analytical solutions can help us to understand different regimes or aspects of hydrodynamics locally, they are extremely limited in actual application because of the very complex boundary conditions and the difficulties in solving the non-linear time-dependent equations in the general case. The analytical solution for prescribed boundary conditions within a domain in space and time are impossible to obtain. In such situation, numerical model can help to get the solution. Numerical models give the solution numerically at discrete space-time points in the domain by approximating the continuous analytical equations by the equations that connect the numerical solution at the selected points (Price, 1999). There are numerous numerical models with discretisation schemes can give solutions that are sufficiently close to the analytical solutions. For instance, the system of equations 3.1 can be solved to get the suitable solution that approximates the analytical solution by using the finite difference method with the four-point implicit Preissmann scheme through the use of the operators

$$\begin{aligned} \frac{\partial f}{\partial t} &\approx 0.5 \frac{f_{i+1}^{n+1} - f_{i+1}^n}{\Delta t} + 0.5 \frac{f_i^{n+1} - f_i^n}{\Delta t} \\ \frac{\partial f}{\partial x} &\approx \theta \frac{f_{i+1}^{n+1} - f_i^{n+1}}{\Delta x} + (1 - \theta) \frac{f_{i+1}^n - f_i^n}{\Delta x} \end{aligned} \quad (3.6)$$

In the context of the computational methods, computer technology and industry are developed rapidly, the numerical models are developed and applied intensively with the state-of-the-art models, robust but easy to use. In 1D modelling, there are several commercial engines using different forms of finite difference equations.

In this study, with only concerning to inlet and lagoon flow dynamics that is contingent upon several factors including inlet and lagoon geometry, bed roughness characteristics, freshwater flow, ocean tide characteristics, an 1D numerical model named DUFLOW is available and can be used. Section 3.5.2 will introduce to the DUFLOW model that is chosen for hydrodynamic analysis of the study.

3.3. TIDAL INLET MORPHOLOGY AND PROCESSES

Many studies in coastal geomorphology and engineering have focused on the modes of tidal inlet formation, morphology, and migration. This section presents an overview of geomorphic

models for tidal inlets, their processes of formation, and relevance to migration and behaviour.

Hayes (1967) and Pierce (1970) documented inlet formation by the seaward return of storm-surge breaching narrow areas along a barrier island. In this manner, narrow, shallow, ephemeral inlets are formed during hurricanes and migrate in the downdrift direction. If the tidal prism is unable to maintain these hurricane-generated inlets, landward swash-bar migration and overwash seal the inlet mouth. Inlets whose origin can be attributed to storm processes generally occur in microtidal (wave-dominated) settings. The present Tu Hien inlet of the Tam Giang-Cau Hai lagoon can be seen as belonging to this kind of inlet but the floods take the main acting force instead of storm-surges.

3.3.1. Geomorphic models

The interaction of wave regime and tidal range has a profound effect, not only on the morphology, but also on the migration and behaviour of tidal inlets and barrier islands. In microtidal settings, long, narrow, wave-dominated barriers extend for tens of kilometres and are separated by ephemeral, rapidly migrating tidal inlets. The associated flood-tidal deltas, deposited by waves and tidal currents, form large, lobate sand bodies in the lagoon. Wave energy and flood-tidal currents exert more influence on sedimentation than ebb currents; therefore, ebb-tidal delta development is poor. Wave-dominated inlets migrate laterally along the shoreline in a downdrift direction for many kilometres and at relatively rapid rates. As the hydraulic efficiency of the inlet decreases, wave-reworked ebb-tidal delta sands accumulate in the inlet mouth, resulting in closure of the inlet channel and abandonment of the flood-tidal delta (USACE, 1989).

Unlike wave-dominated coasts, tidally influenced mesotidal barriers often assume a stunted, drumstick-shaped configuration. These barriers are wider, extend for several kilometres, and are separated by numerous, more stable tidal inlets. The back-barrier lagoon and flood-tidal delta of the wave-dominated shoreline are replaced by salt marsh and tidal creeks. Tidal current dominance over wave energy helps to confine these inlets, restricting downdrift migration to less than 2 km (USACE, 1989). Tidally influenced inlet channels are deflected downdrift by preferential addition of sand to the updrift lobe of the ebb-tidal delta. These inlet channels lose hydraulic efficiency and breach the barrier to form a shorter updrift channel. Large sediment lobes are reworked from the former ebb-tidal delta and eventually weld onto the barrier, closing the earlier inlet channel. Landward, out of the influence of wave transport, silt and clay accumulate in the former channel due to the absence of strong tidal currents.

3.3.2. Inlet migration processes

As explained by Bruun (1990), most inlets on littoral drift shores naturally migrate alongshore in the direction of the prevailing littoral drift. The migration rate of inlets on sandy coasts depends on several factors including wave climate, tidal range, depth of the main channel, the phase difference between any long-shore tidal current and the tidal currents in the inlet, nature of the substrate into which the channel is incised, sediment supply, and rate of longshore sediment transport. As a result of deposits on the updrift side, the inlet channel is usually forced to move in downdrift direction causing erosion downdrift. By this process the updrift barrier may extent seaward in front of the downdrift barrier or land area overlapping it.

Such a situation is time-limited. Continued extension of the channel by deposits increases head losses, and the inlet may finally close. Closing often happens in connection with the breakthrough of a new inlet through the barrier making a shorter, and from the hydraulic standpoint, more “practical” ocean connection. Such a breakthrough may be a result of erosion or of a storm tide or by a river flood. In many cases, the breakthrough happens because the barrier was flooded by storage water in the bay or lagoon and could not escape fast enough through the “long” channel.

The developments of the Thuan An and Tu Hien inlets are somehow similar to the process described above.

3.3.3. Natural sediment bypassing

Inlet sediment bypassing is the transport of sediment (sand) from the updrift to the downdrift margin of the tidal inlet. This process is fundamental to understanding and predicting shoreline erosion and deposition trends in areas adjacent to the tidal inlet. Bruun and Gerritsen (1959) first described the natural mechanisms of inlet sediment bypassing and related the variables involved in this process using the equation:

$$r = \frac{M_{mean}}{Q_{max}} \quad (3.7)$$

where

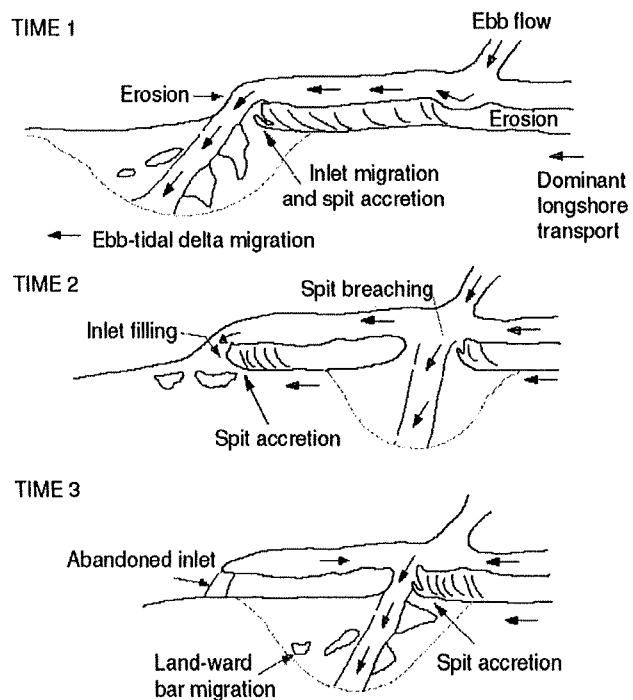
M_{mean} is the average rate of long-shore sediment transport to the inlet and Q_{max} is the maximum discharge to the inlet during spring tidal conditions.

As explained by Bruun and Gerritsen (Bruun and Gerritsen, 1960), the dimensionless parameter $r = M_{mean}/Q_{max}$ seems to be significant for the magnitude of by-passing. The value of this ratio indicates whether by-passing is predominantly a “bar” or a “tidal flow” transfer. Bruun and Gerritsen defined three methods by which sand “bypasses” tidal inlets: (a) by wave-induced sand transport along the outer margin of the ebb-delta (terminal lobe), (b) through transport of sand by tidal currents in channels, and (c) by the migration and accretion of sandbars and tidal channels. By the latter method, material is flushed out of the inlet by ebb currents carrying the material away from the inlet entrance to the offshore area, possibly in downdrift direction. From practical experience with by-passing, the following rule may be used as a guide:

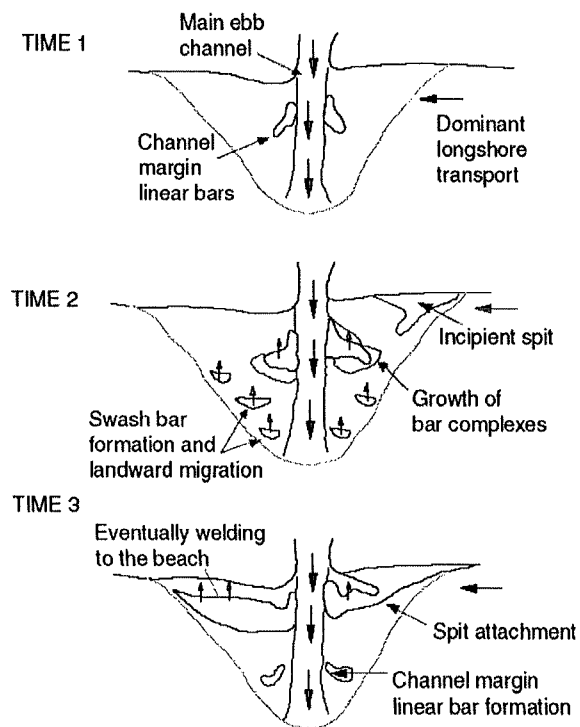
- $r < 10 - 20$ indicates predominant tidal flow by-passing (little or no bar formation) (bypass sand through methods (b) and (c)),
- $r > 200 - 300$ indicates predominant bar by-passing with typical bar or shoal formation.

Subsequent field studies by geologists refined the original concepts of Bruun and Gerritsen. FitzGerald (1988) proposed three models to summarise the mechanisms of tidal inlet migration through sediment bypassing on microtidal and mesotidal coasts. These models are shown in Figure 3.2 and are summarised as follows (USACE, 1989; De Vriend *et al.*, 2000).

MODEL 1 - Inlet migration and spit breaching



MODEL 2 - Stable inlet processes



MODEL 3 - Ebb-tidal delta breaching

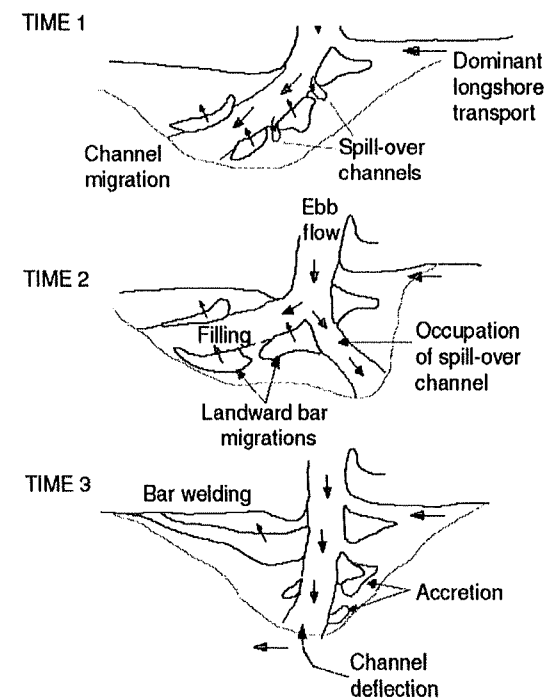


Figure 3.4. Models of inlet sediment by-passing

- **Model 1 – Inlet migration and spit breaching:** Extensive and/or rapid channel migration is generally associated with relatively shallow tidal inlets while deeper tidal inlets are less likely to migrate as they have a greater probability of incising into semi-consolidated sediments. Migration and spit breaching are more common to wave-dominated tidal inlets. However, if the tidal prism is small enough, or where the backbarrier is infilled with salt marsh and tidal flats, as is characteristic of mesotidal shorelines, migration of the inlet often results in a shore-parallel elongation of the inlet channel. In such cases, a storm or hurricane will breach the updrift part of the spit and establish a more hydraulically efficient inlet.
- **Model 2 – Stable inlet processes:** Stable inlets have an inlet throat and main ebb channel that do not migrate. Migration in these inlets can be restricted by antecedent topography or incision into semi-consolidated material. Inlets of this type can occur in any hydrographic setting but are more commonly associated with bedrock-controlled inlets or those that can attribute their origin to ancestral distributary channels. Sand bypassing at these inlets occurs through the landward migration and accretion of large bar complexes to the downdrift margin (Hine, 1975)
- **Model 3 – Ebb-tidal delta breaching:** Ebb-tidal delta breaching through bar-bypassing is the major process of channel migration and abandonment at tide-dominated inlets. Tidal inlets associated with this process have a stable inlet throat, but the main ebb channel migrates or “pivots” with time. Migration occurs through downdrift over-extension of the main ebb channel and subsequent breaching of a shorter updrift channel. Ebb-delta breaching and bar bypassing occur rapidly at smaller inlets (Sexton and Hayes 1982), but one cycle of inlet channel migration and abandonment may take over 100 years (Tye 1984).

3.3.4. Tidal deltas

The overall morphology of ebb- and flood-tidal deltas is a function of the interaction of tidal currents and waves. Especially important is the phenomenon of time-velocity asymmetry of tidal currents. As described by Postma (1967), maximum ebb- and flood-tidal current velocities do not occur at mid-tide. Of critical significance is that maximum ebb currents typically occur late in the tidal cycle, near low water. This means that at low water, as the tide turns, strong currents are still flowing seaward out of the main ebb channel. As water level rises, flood currents seek the paths of least resistance around the margin of the delta. This process creates the horizontal segregation of flood and ebb currents in the tidal channels that ultimately moulds and shapes the tidal deltas.

Variations in flood- and ebb-tidal delta morphology are a function of tidal prism, backbarrier morphology, and relative wave energy. Patterns of sand transport on tidal deltas are quite complex and very difficult to measure in the field. However, Hine (1975) and Imperato, Sexton, and Hayes (1988) based on mapping tide- and wave-generated current transport pathways and concluded that proximal parts of the deltas (main ebb and flood marginal channels) are dominated by tidal currents, whereas distal portions (periphery) are dominated by wave- (swash) generated currents.

3.4. INLET STABILITY CRITERIA

According to Bruun (1990), any tidal inlet on a littoral drift shore presents as integrated result of forces by flow, waves and sediment transport balancing each other in a state of “dynamic equilibrium”.

Some inlets are permanent and remain open with relatively small changes in location, cross-sectional area, and shape; others are ephemeral or subject to intermittent openings and closings. The ability of an inlet to maintain itself in a state of stable equilibrium against wave activity and associated littoral transport depends on the availability of littoral material and the tidal prism.

3.4.1. Cross sectional area versus tidal prism empirical relationship

Many attempts at describing inlet stability have concentrated on empirical relationships between the tidal prism and inlet throat cross-sectional area (LeConte 1905; O'Brien 1931, 1969; Nayak 1971; Johnson 1973).

O'Brien (1931, 1969) introduced a diagram relating cross-sections to tidal prism. Attempts to correlate inlet flows to inlet sedimentary stabilities have been few and meager (Bruun, 1990).

Jarrett (1976) reviewed the previously established relationships and performed a regression analysis on data from 108 inlets in Pacific, Atlantic, and gulf coasts in various combinations in an attempt to determine best-fit equations. Results of his analysis indicated that the tidal prism-inlet (P) cross-sectional area (A) relationship is not a unique function for all inlets, but varies depending on inlet location and the presence or absence of jetties. Jarrett confirmed the original relationship established by O'Brien (1969) for inlets with two jetties

$$A = 4.69 \times 10^{-4} P^{0.85} \quad (3.8)$$

and concluded that natural inlets and single-jettied inlets on the three coasts exhibit slightly different P versus A relationships due to differences in tidal and wave characteristics.

3.4.2. Cross sectional stabilities

Escoffier (1940) introduced a hydraulic stability curve, referred to as the Escoffier diagram, on which maximum velocity is plotted against cross-sectional flow area. A single hydraulic stability curve represents changing inlet conditions, when ocean tide parameters, and bay and inlet plan geometry conditions remain relatively fixed. If these conditions are drastically altered, a new stability curve is established. Each position on the curve represents a different value of Keulegan's repletion coefficient K , the ratio of bay to ocean tidal amplitude, and tidal phase lag between ocean high or low tide and slack water in the inlet.

According to the Escoffier diagram, an inlet is hydraulically stable if its cross-sectional area is larger than the critical flow area A_{c*} . An induced change in the cross-sectional area of a stable inlet will result in a change in inlet velocity that attempts to return the inlet to its equilibrium size by appropriate deposition or scour.

An inlet having a cross-sectional area smaller than the critical flow area is termed hydraulically unstable. The Escoffier diagram illustrates that any change in flow area is accompanied by a change in flow velocity that will perpetuate the induced change. Since any

initial change in flow area is accentuated, the hydraulically unstable inlet will either continuously scour until the critical flow area is attained, or continuously shoal until inlet closure.

Escoffier's hydraulic stability model has been applied in describing the behavior of "hydraulically stable" inlets by O'Brien and Dean (1972); Defenr and Sorensen (1973); and Mehta and Jones (1976). Escoffier's approach (Escoffier, 1940, 1980) is still only a "static" approach concentrating solely on the gorge channel not including the hydrodynamic interaction between flows and sediment transport. Wave action and river flow are non-existing (Bruun, 1990).

O'Brien and Dean (1972) proposed a method of calculating the effect of deposition on stability of an inlet. Their method is based on earlier contributions by O'Brien (1931), Escoffier (1940), and Keulegan (1967), and assumes that a critical cross-sectional throat area A_c^* exists with a corresponding critical velocity V_{max} . A stability index β represents the capacity of an inlet to resist closure under conditions of deposition. It incorporates the buffer storage area available in the inlet cross section, prior to deposition, and also includes the capability of the inlet to transport excess sand from its throat. Inlets with an equilibrium area much larger than the critical area have more storage area, and therefore, will be more resistant to change.

According to Bruun (1990), any stability consideration at tidal inlets must be related to the amount of drift transferred to the inlet from the sides. If this drift is small, no strong currents are needed to flush a normal tidal entrance not receiving any material from landward sources by stream flow. Bruun (1967, 1968, 1978) gave some pertinent values for 11 tidal inlets, eight with semi-diurnal or mixed tides and three with diurnal tides.

To evaluate the stability in various ways, the determining shear stress $T_s^* = \rho g \left(\frac{V_{max}}{C} \right)^2$ was computed as well as the V_{max} , and $V_{mean} = \frac{2V_{max}}{\pi C_1}$ (Keulegan, 1950) and finally checked with $V_{mean} = \frac{2P}{AT}$. With the fact that most of the inlets are of the semi-diurnal type, the actual velocities obtained $V_{mean\ max}$ is about 0.99 m/s and V_{mean} is about 0.7 m/s

Bruun and Gerritsen's first works (1960) concentrated on the "gorge stability", too, and tried to explain why the mean maximum velocity for the flow in the gorge section at spring tides always seemed to stay close to 1 m/s. Bruun *et al.* (1974) concluded that $V_{mean\ max}$ at spring tide seems to be a useful parameter for description of the cross sectional stability of a tidal inlet entrance channel.

3.4.3. The P/M_{tot} criteria

Bruun and Gerittsen were among the first to note the "large scale stability" of tidal inlets on littoral drift shores (Bruun and Gerittsen, 1960). According to them, the difference in behaviour of tidal inlets on downdrift erosion could be described largely by considering the ratio between the maximum discharge volume Q_{max} and the predominant drift quantity M_{mean} to the entrance in Equation 3.7. Later (Bruun, 1968, 1978, 1986) this ratio was converted to the P/M_{tot} . P/M_{tot} seems to describe well the "overall stability". According to Bruun (1968, 1978, 1990), the P/M_{tot} is a "sensible parameter" for the overall stability.

The P/M_{tot} criteria for inlet stability, where M_{tot} is the total annual littoral drift ($m^3/year$), and P is the tidal prism ($m^3/tidal\ cycle$), were introduced by Bruun and Gerritsen (1960) and elaborated on by Bruun (1978). The stability of an inlet is rated as good, fair, or poor according to the Table 3.3 following:

Table 3.3. The overall criteria for inlet stability in terms of by-passing capacity

$\frac{P}{M_{tot}}$	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

Table 3.4. Entrance conditions in relation to $\frac{P}{M_{tot}}$ (Bruun,1990)

$\frac{P}{M_{tot}}$	Entrance conditions
>300	Little or no ocean bar outside gorge (cean shoals may occur further out)
$150 - 300$	Little ocean bar
$100 - 150$	Low ocean bar, navigation problems usually minor
$50 - 100$	Wider and higher ocean bar, increasing navigation problems
$20 - 50$	Wide and shallow ocean bar, navigation difficult
< 20	Very shallow ocean bar, navigation very difficult

According to Bruun (1990), overall stability must include all sections of a tidal entrance as divided by Bruun (1978) in ocean bar, gorge, and the intermediate section. Because each of these sections is influenced by combinations of currents and wave forces, their sediment transports need to be considered accordingly.

The analysis of the inlet stability using Bruun criteria for the Tam Giang-Cau Hai lagoon will be discussed in Chapter 6.

3.5. NUMERICAL MODELING OF TIDAL INLETS

Coastal phenomena such as waves, currents, water levels, flow discharge, water quality, and sediment transport can be numerically simulated at inlets to predict impacts of existing or proposed design alternatives. For example, it may be necessary to maintain or improve inlet characteristics such as water quality, channel navigability, structural integrity, channel

shoaling rates, and sediment bypassing strategies for a particular inlet configuration or maintenance plan. By comparing existing coastal processes to those simulated, effects of design plans and operation and maintenance practices can be assessed and optimised.

Typically, models may be employed to improve our understanding of various phenomena at prototype locations and to furnish explanations for observed behaviour or failure. They are often used to compare existing (base) conditions to future plan conditions and thereby predict the impact of plans on hydrodynamics (velocities, discharges, water levels), water quality, and sediment transport at key locations. By testing alternate plans in the numerical models, it is possible to assess the advantages and disadvantages of each and choose from among the alternatives the best for project implementation. It may be necessary to ensure that for the design selected, velocities in the interior are adequate for mixing and flushing, velocities and waves near the navigation channel do not adversely impact navigation, and velocities near structures are sufficiently low to prevent scour. Examples of such projects are navigation channel modifications and jetty construction for channel stabilisation. Often, the designer is faced with conflicting requirements. For instance, by increasing jetty spacing, velocities in the navigation channel may be reduced, thereby improving navigation but worsening channel shoaling, and vice versa. Model results enable the designer to strike a balance. In light of model testing, improved designs and modifications to original designs can result. One area where significant cost reductions may be possible is in estimating maintenance dredging required after channel modifications. Using model predictions of advance maintenance dredging required for different reaches of channel, it is possible to modify the channel design and reduce the overall dredging required. Even though they are approximate, numerical models are the only tools available to predict sediment transport quantitatively in such cases.

3.5.1. Physical processes considered

The following physical processes are usually considered in numerical modelling of tidal inlets under non-storm conditions: astronomical tides, winds, short period waves, freshwater flows, and sediment transport. Under hurricane and storm conditions, the effects of storm surge also have to be accounted for.

3.5.1.1. Astronomical tides

Tides can be a major forcing mechanism at inlets. Tides are long-period waves, which can be predicted accurately along the open coast using results of harmonic analysis of measured water level fluctuations. Near inlets and in the interior, numerical models must be used for tidal prediction because of the complex interactions between bathymetry, inlet and back-bay geometry, proximity of structures, and interconnection with other inlets. Tides change currents and water levels, which are important for circulation and sediment transport.

3.5.1.2. Winds

Winds induce a change in water level (wind set-up) and currents, the magnitude of which depends on wind speed and direction. Water level increases in the direction of the wind. Currents are in the direction of the wind at the surface, but direction and magnitude may vertically vary. Wind effects are usually accounted for in either a tidal or a wave-induced current model.

3.5.1.3. *Short-period waves*

Short-period ocean waves are represented near inlets either by a monochromatic wave (e.g., significant wave) or a wave spectrum. In the first approach, individual waves are characterised by wave height, period, and direction. In the second approach, a wave with a specified height is characterised by the distribution of energy in different frequency (period) and direction bands. Short waves result in changes in water level (wave setup) and wave-induced currents (longshore and rip currents) near inlets which cause not only changes in flow pattern, but also sediment transport. Wave orbital velocities at the bed cause increased shear stresses, resulting in greater sediment transport. Because of the complex transformation processes which take place in the near-shore, short waves are predicted near inlets using numerical models of the monochromatic or spectral type. In either case, the wave characteristics in deeper water are either measured in the field, or obtained from forecast or hindcast performed using a spectral model.

3.5.1.4. *Freshwater flows*

Freshwater flows into the back-bay (lagoon) system from rivers and creeks influence both flow patterns and salinities and contribute to the flushing in the inlets. Freshwater flows have to be specified at the boundaries of the numerical model grid.

3.5.1.5. *Sediment transport*

Magnitude and direction of inlet sediment transport depend on the processes of tides, winds, waves, and freshwater flows. Sediment transport at inlets is of major concern to coastal engineers and planners, because its rate and distribution through the inlet affect many processes of engineering concern (e.g., channel shoaling rates, erosion/accretion of interior (bay, lagoon) and ocean (adjacent) inlet shorelines, stability of structure foundations (jetties, bridge pilings), etc.). Modifications which change the existing transport rates and patterns can disrupt the integrity and viability of a stabilised, navigable inlet. Typically, sediment transport in the back bay is characterised by cohesive materials such as clays, silts, and fine sands, whereas transport in the region offshore of the inlet throat is characterised by noncohesive materials such as sand and shell. Usually, sediment transport models use the results of hydrodynamic models for input.

3.5.2. **DUFLOW model**

In general, inlet flow dynamics is contingent upon several factors including inlet and lagoon geometry, bed roughness characteristics, freshwater flow, ocean tide characteristics and ocean wave characteristics and sediment movement. A combination of these factors can produce a rather complex situation (Mehta, 1978).

As a reconnaissance level of the study on the hydrodynamics of the Tam Giang-Cau Hai lagoon and tidal inlet system, only the effects of inlet and lagoon geometry, freshwater flow, variation of sea water level and ocean tides are considered in the scope of this study. Effects of winds, waves, density currents and sediment transport are left outside. With this target, a numerical model named DUFLOW that is available and can be used for the study.

DUFLOW is a one-dimensional model for unsteady flow computations in networks of open watercourses. The model is developed by three institutes in the Netherlands: the International Institute for Infrastructure, Hydraulic and Environmental Engineering (IHE), Delft; the

Rijkswaterstaat (Public Works Department), Tidal Waters Division, the Hague; and the Delft University of Technology (TU Delft), Faculty of Civil Engineering.

The model solves the system of 1D partial differential equations 3.1 for unsteady flow in open channels using the four-point implicit Preissmann finite difference scheme as described in Equation 3.6.

DUFLOW computes flow conditions in channels accepts the variety channel geometry and channel friction in both channel longitudinal and transverse directions, and the variety of boundary conditions. The inlet to be modelled may consist of a single channel connecting the sea to the bay, or it can be a system of interconnected channels, with or without bays. Values of water surface elevation, flow discharge and cross-sectional average velocity are computed at locations along inlet channels. The model is suited for reconnaissance-level studies for most inlets, providing reliable and accurate answers with minimal data entry and grid generation. Besides unsteady hydraulic simulating of open channel sections (both river and canal sections), the model can simulate other control sections or structures such as weirs, culverts, siphons and pumps, and water quality.

With the use a 1D hydraulic numerical model such as DUFLOW that is based on the Saint-Venant system of equations 3.1, the following common assumptions are accepted:

1. The flow is one-dimensional, that is, the velocity is uniform over the cross section and the water level across the section is horizontal.
2. The streamline curvature is small and vertical accelerations are negligible, hence the pressure is hydrostatic distributed.
3. The effects of boundary friction and turbulence can be accounted for through resistance laws analogous to those used for steady state flow.
4. The average channel bed slope is small so that the cosine of the angle it makes with the horizontal may be replaced by unity.
5. The flow is incompressible, density differences are negligible, as are a whole number of other effects.

The assumption above of one-dimensionality is crude but effective and generally reasonable and accepted (Price, 1999).

Chapter 4. BASIC DATA COLLECTION AND PROCESSING

4.1. INTRODUCTION

With the purposes, the scope, the methodology of the study that are stated in Chapter 1 and the DUFLOW model tool is chosen for study the hydrodynamics of the Tam Giang-Cau Hai lagoon and tidal inlet system at a reconnaissance level, the relevant data for this study that are collected are geometry and bathymetry of the lagoon and tidal inlets; topography and cross section of the rivers; tidal water levels; flow discharges, flow velocities and water levels in the rivers and in the system. For inlet stability analysis, information about waves and sediment transport are also collected.

The national standard reference level is referred to Hon Dau Datum (HD). Hon Dau Datum is about 0.14m above mean sea level (MSL). Hon Dau Datum is used and is referred as the standard reference level throughout in this study.

4.2. TIDAL WATER LEVEL

The tidal water levels are needed for the boundary conditions at the three inlets of Thuan An, Hoa Duan and Tu Hien in the sea. But there is no permanent tidal station for observation of sea water level in the province.

For this study, the observed data of tidal water level in the area at the inlets is available only in very short periods:

- At Thuan An: from 14/4/1999 to 23/4/1999 and from 7/5/2000 to 17/5/2000
- At Hoa Duan: from 17/4/1999 to 23/4/1999 at Eo Bau (Hoa Duan trait) and from 7/5/2000 to 17/5/2000
- At Tu Hien: from 7/5/2000 to 17/5/2000

The observed data from 14/4/1999 to 23/4/1999 at the Thuan An inlet have a very low accuracy. The gauge was checked for its reference level every 4 days, at 1h00 18/4 and 7h00 22/4/1999. But at the check of 7h00 22/4/1999, a big error was found because the HW was also the LW of the following tidal cycle as can be seen in Figure 4.4.

The maximum tidal range at the Tu Hien inlet in the observation period from 7/5/2000 to 17/5/2000 is only 0.30 m, is quite small in comparison with the tidal range from literature of 0.55 – 1.0 m in this area. The reason may be the measurements were taken in the inlet at a location that was too far the open sea and behind a shoal area.

These available data of tidal water level are too short to use in tidal analysis to determine tidal constants of even main constituents. The minimum observation period to separate four main components of M_2 , S_2 , K_1 and O_1 is 15 days. The period of 30 days is more or less accepted as the standard observation period for a minimum tidal analysis. The period of 369 days is considered as the standard length for a tidal analysis because nearly all of tidal components including long periodic constituents can be separated (Roos, 1997).

Therefore, it is necessary to generate data for the boundary conditions at the inlet locations. The data that can be used are astronomic tides obtained by tidal analysis and prediction methods. The tidal water level at the inlets can be computed based on an appropriate reference station such as Da Nang or Cua Viet, or using tidal constants computed from the observed data at the inlets themselves.

4.2.1. Possibility of using a reference tidal station

At Da Nang station located about 80 km south east of the inlets, astronomic tidal water levels can be predicted by using tidal prediction programs such as XTide or using tide tables. With a tidal program likes XTide, water level at Da Nang can be generated and then water levels at Thuan An, Hoa Duan and Tu Hien inlets can be computed using known relationships of the water levels at these locations with water level at Da Nang station.

XTide is used to investigate the possibility of using a reference tidal station. In the used version of XTide, tidal water level at Da Nang (mixed, mainly semi-diurnal) can be predicted with 37 constituents from the Table des Marees des Grands Ports du Monde. In fact, in this program, water level at Da Nang is computed using the reference tidal station of Manila (mixed, mainly diurnal) in the Philippines but not using the tidal parameters of the station itself. So there is a difference in phase of 6 hours between the tides predicted by XTide and water level in the Tide Tables published annually by HMS.

Therefore, tidal water level at Da Nang station is not predicted using XTide but can be computed using Equation (4.1) in an MS Excel spreadsheet (see also Roos, 1997; Verhagen, 1999).

$$Z(t) = Z_0 + \sum_{i=1}^n f_i H_i \cos(\omega_i t + v_i + u_i - g_i) \quad (4.1)$$

where	$Z(t)$	tidal water level (m)
	Z_0	mean water level (m)
	f_i	node factor of the constituent i
	H_i	amplitude of the constituent i (m)
	ω_i	angular speed of the constituent i (degrees/hour)
	$v_i + u_i$	equilibrium argument (degrees)
	g_i	harmonic constant (degrees)

The result is then compared with the water level published by HMS in tide tables using Nash-Sutcliffe criteria:

$$R^2 = 100 \frac{F_0^2 - F^2}{F_0^2} (\%) \quad (4.2)$$

with

$$F_0^2 = \sum_{j=1}^m (Z_j - \bar{Z})^2 \quad (4.3)$$

$$F^2 = \sum_{j=1}^m (Z_j - \hat{Z}_j)^2 \quad (4.4)$$

$$\bar{Z} = \frac{1}{m} \sum_{j=1}^m Z_j \quad (4.5)$$

where Z_j is observed value and $\hat{Z}_j$ is computed value. $R^2 = 100\%$ if all computed values are identical to the observed values.

The results of computation astronomic tides at Da Nang using Equation (4.1) in Excel are shown in Figure 4.1 and Figure I.7 in Appendix I. These results in comparison to the tide table published by HMS give a close agreement with $R^2 = 97\%$. So, it can be concluded that the tidal constants of Da Nang station from the Table des Marees des Grands Ports du Monde are still valid and can be used for tidal prediction with Equation (4.1).

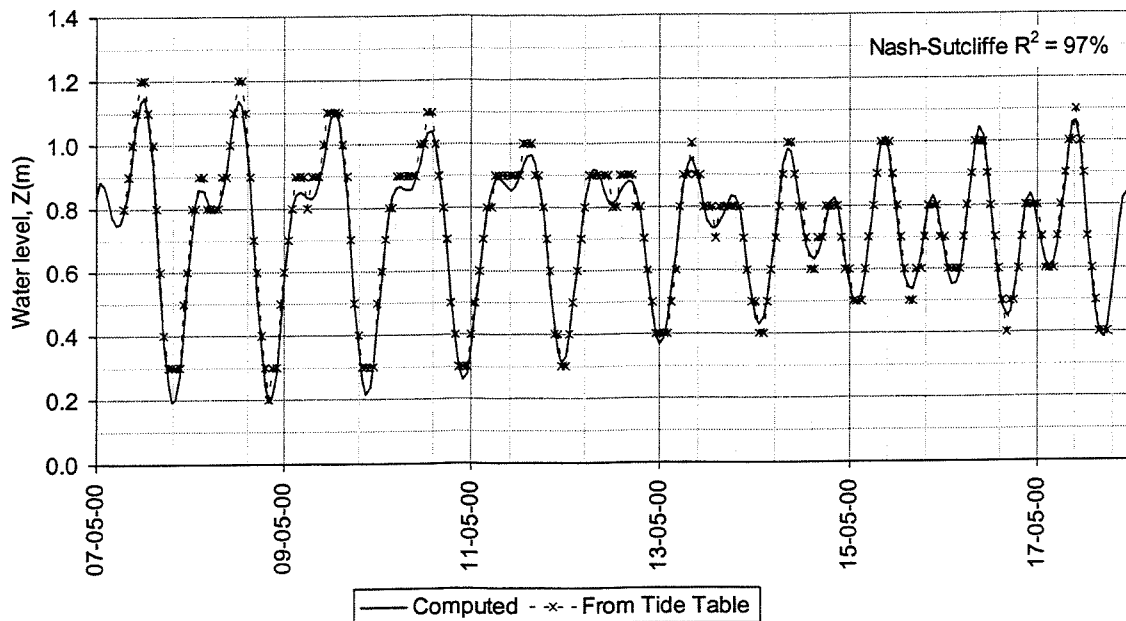


Figure 4.1. Astronomic tides in May 2000 at Da Nang station

Unfortunately, the type of tides at the inlets is different to any location in the surrounding area. As can be seen in Figure I.7 in Appendix I, tides at the inlets are fully semi-diurnal while they are mixed, mainly semi-diurnal in the surrounding areas (Da Nang, Cua Viet). So the relationships between the tidal water levels at the inlets and the tidal water level at Da Nang are very weak as can be seen in Figure I.8 to Figure I.10 in Appendix I.

4.2.2. Possibility of using tidal constants computed from observed data

To compute water level for the boundary conditions at the locations of the inlets, it is better to compute tidal constants from observed data at these locations and use them for tidal prediction.

Because the observation periods of the measured data at the inlets are too short to decompose even some main tidal constituents using tidal analysis methods, the approach of optimisation is used to get the tidal constants at these locations. The objective function of the optimisation problem is to minimise the sum of squared error between computed and observed data points. The optimum solution is then searched for using Microsoft Excel Solver with the Generalised Reduced Gradient (GRG2) non-linear optimisation method and the tidal constants of Da Nang station are used as initial guesses. This method does not give a unique solution because of the non-linear problem, but the result is checked and verified with the tidal range in reality to get a reasonable solution.

Following this approach, the tidal constants at the Thuan An inlet and Tu Hien inlet are determined using the observed water level at these locations from 7/5/2000 to 17/5/2000. The initial guess is taken from the tidal constants of Da Nang station. The tidal constants that are computed by this approach are shown in Table 4.1.

The tidal constants of the Thuan An inlet are determined based on observed data of 2000 with $R^2 = 86\%$ (Figure 4.3) and then are checked with observed data in 1999 giving $R^2 = 75\%$ (Figure 4.4).

The computed tidal water level in comparison with observed data at the Tu Hien inlet in 2000 is shown in Figure 4.5 with $R^2 = 92\%$.

From the results in Table 4.1, most values of important diurnal constituents (e.g. K1, P1, Q1) are very small at Thuan An and Tu Hien in the fully semi-diurnal area while these values are significant at Da Nang station in a mixed, mainly semi-diurnal tidal regime. The tide can be classified by the form number defined as (see Dronkers, 1964; Roos, 1997; Verhagen, 1999)

$$F = \frac{H_{K1} + H_{O1}}{H_{M2} + H_{S2}} \quad (4.6)$$

According to the value of F, four types of tides can be distinguished

- $F < 0.25$: fully semi-diurnal;
- $0.25 < F < 1.5$: mixed, mainly semi-diurnal;
- $1.5 < F < 3$: mixed, mainly diurnal;
- $F > 3$: fully diurnal.

The form numbers at Thuan An and Tu Hien are $F=0.20$ and $F=0.10$, respectively, are less than 0.25, i.e. tides at these locations are fully semi-diurnal. Where the form numbers at Da Nang is $F=1.41$, that is mixed, dominant semi-diurnal tide. At Manila, the form number is $F = 2.15$, has mixed, dominant diurnal tide (Roos, 1997).

These improve the difference in tidal regime of the inlets and Da Nang station as stated in Section 4.2.1.

The sensitivity of the tidal constants to the computed result of the model will be checked out in Chapter 6.

Table 4.1. The tidal constants at Da Nang, Thuan An and Tu Hien

Tidal constituent			Da Nang		Thuan An		Tu Hien	
	ω (°/hour)	Type	H (m)	g (°)	H (m)	g (°)	H (m)	g (°)
J1	15.5854433	Smaller lunar elliptic diurnal	0.010	312.8	0.003	312.8	0.005	312.8
K1	15.0410686	Diurnal lunar-solar declination	0.195	290.0	0.044	290.0	0.025	290.0
K2	30.0821373	Semi-diurnal lunar-solar declination tide	0.016	343.2	0	343.2	0.139	343.2
L2	29.5284789	Smaller lunar elliptic semi-diurnal	0.005	327.0	0	327.0	0.104	327.0
M1	14.4966939	Smaller lunar elliptic diurnal	0.009	267.0	0.012	267.0	0	267.0
M2	28.9841042	Semi-diurnal principle lunar	0.172	301.0	0.120	301.0	0.153	301.0
M3	43.4761563	Lunar terdiurnal constituent	0	0.0	0	0.0	0.001	0.0
M4	57.9682084	Shallow water overtides of principal lunar constituent	0.005	258.0	0.008	258.0	0.001	258.0
M6	86.9523126		0	0.0	0.001	0.0	0.004	0.0
M8	115.9364169		0	0.0	0	0.0	0.002	0.0
N2	28.4397295	Semi-diurnal lunar elliptic tide	0.037	275.0	0.023	275.0	0.020	275.0
2N2	27.8953548	Lunar elliptic semi diurnal second-order constituent	0.005	249.0	0	249.0	0	249.0
O1	13.9430356	Diurnal lunar declination tide	0.129	244.0	0	244.0	0	244.0
OO1	16.1391017	Lunar diurnal, second-order	0.006	336.0	0	336.0	0.006	336.0
P1	14.9589314	Diurnal solar declination tide	0.065	286.6	0.010	286.6	0.011	286.6
Q1	13.3986609	Larger lunar elliptic diurnal	0.021	234.0	0	234.0	0.009	234.0
2Q1	12.8542862	Lunar elliptic diurnal, 2 nd order	0.003	198.4	0	198.4	0.001	198.4
R2	30.0410667	Smaller solar elliptic	0	341.6	0.026	341.6	0.017	341.6
S1	15.0000000	Solar diurnal constituent	0	0.0	0	0.0	0.005	0.0
S2	30.0000000	Principal solar semi-diurnal	0.058	340.0	0.097	340.0	0.088	340.0
S4	60.0000000	Shallow water overtides of the principal solar constituent	0	0.0	0	0.0	0	0.0
S6	90.0000000		0	0.0	0.001	0.0	0.001	0.0
T2	29.9589333	Larger solar elliptic	0.003	338.4	0.020	338.4	0.223	338.4
LDA2	29.4556253	Smaller lunar evection	0.001	319.1	0.103	319.1	0.034	319.1
MU2	27.9682084	Variational constituent	0.004	262.0	0	262.0	0.010	262.0
NU2	28.5125831	Larger lunar evectional	0.007	278.5	0.064	278.5	0.055	278.5
RHO1	13.4715145	Larger lunar evectional diurnal	0.005	224.3	0.022	224.3	0.023	224.3
MK3	44.0251729	Combination M2+K1	0	0.0	0	0.0	0	0.0
2MK3	42.9271398		0	0.0	0	0.0	0	0.0
MN4	57.4238337	Quarter diurnal	0	0.0	0	0.0	0.002	0.0
MS4	58.9841042	Combination M2+S2	0.010	262.0	0.005	262.0	0	262.0
2SM2	31.0158958		0	0.0	0.018	0.0	0	0.0
MF	1.0980331	Lunar fort nightly constituent	0	0.0	0.040	0.0	0.018	0.0
MSF	1.0158958	Lunisolar synodic fort nightly	0	0.0	0.007	0.0	0.014	0.0
MM	0.5443747	Lunar monthly constituent	0	0.0	0	0.0	0	0.0
SA	0.0410686	Solar annual constituent	0.181	235.0	0.571	235.0	0.582	235.0
SSA	0.0821373	Solar semi-annual constituent	0	0.0	0.144	0.0	0	0.0

The results of predicted water level at Da Nang, Thuan An and Tu Hien using tidal constants for the year of 2000 are shown in Figure 4.2, Figure 4.4 and Figure 4.3. From Figure 4.2 we can see the variation of water level with the seasons, especially at Thuan An and Tu Hien. This can be explained by the fact that the measurements taken at these locations were inside the inlets, therefore, the water level was effected by the flow from the rivers. From Figure 4.2, the maximum and the minimum value of water level are 1.5 m and -0.5 m, respectively. These values are coincident with the observed data at Thuan An of The Management Board of the Huong River Projects (Nguyen Tuan Anh *et al.*, 1999).

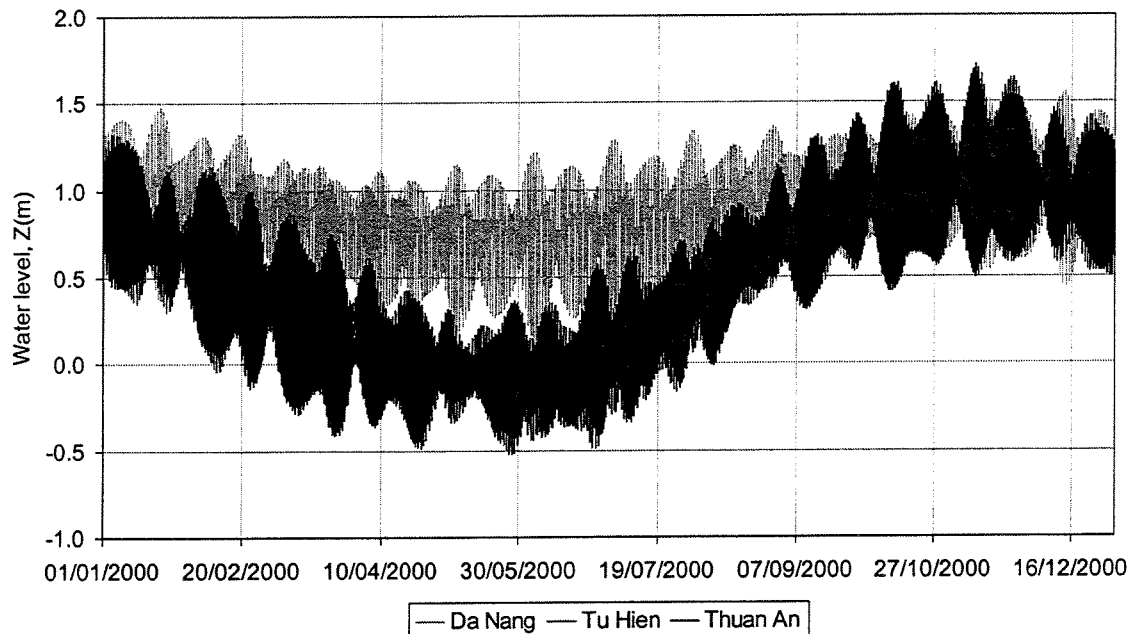


Figure 4.2. Computed tidal water level in 2000

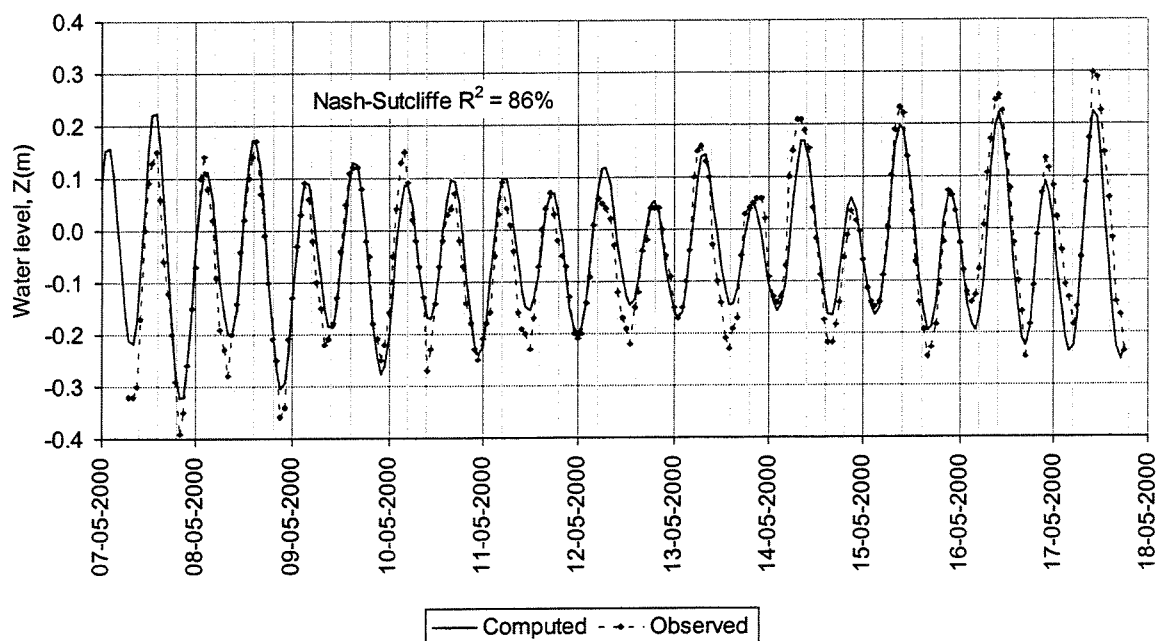


Figure 4.3. Computed tidal water level at the Thuan An inlet in 2000

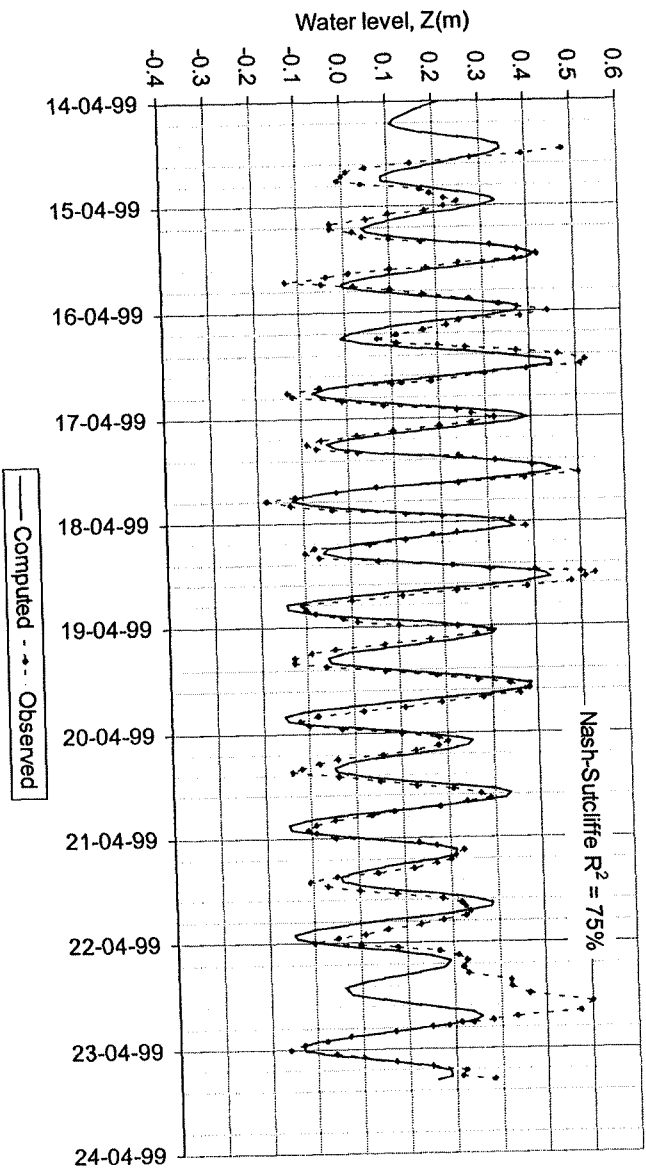


Figure 4.4. Computed tidal water level at the Thuan An inlet in 1999

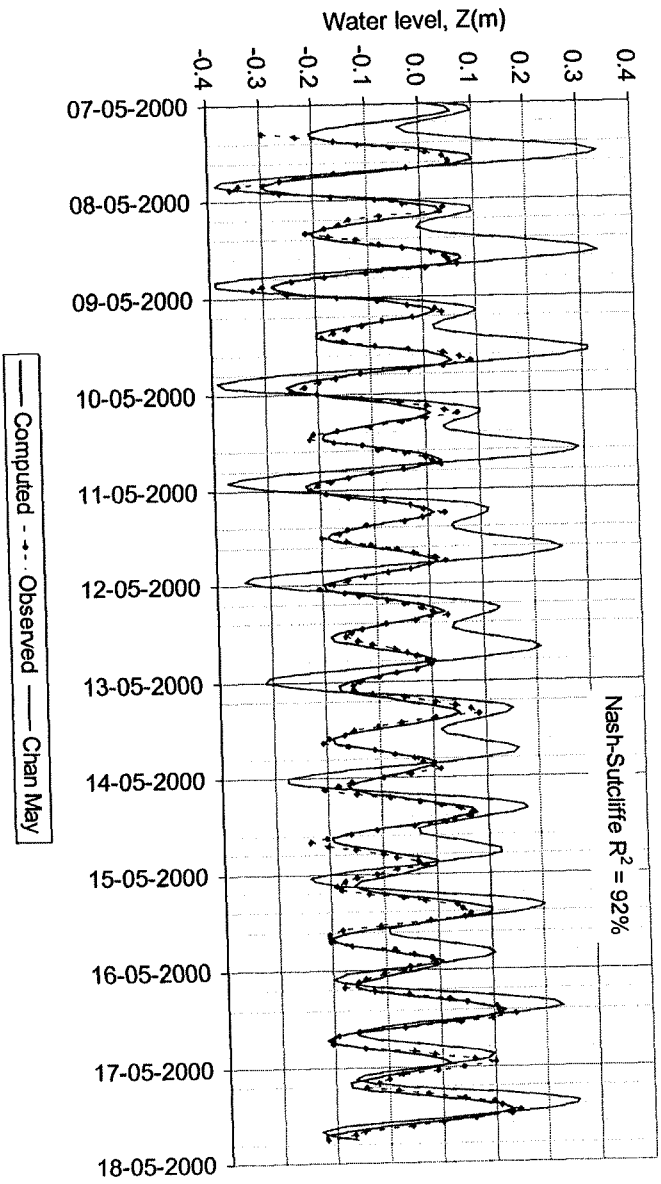


Figure 4.5. Computed tidal water level at the Tu Hien inlet in 2000

4.3. RIVER FLOW DATA

The Tam Giang – Cau Hai lagoon receives flow water of almost rivers in Thua Thien-Hue province, except the Xe Xap River. The Huong River (with its branches are Ta Trach, Huu Trach and Bo rivers) discharges flow water into the lagoon at the main river mouth at Ca Cut near the Thuan An inlet. The other two tributaries of the Huong River have their ends at Ha Do an An Xuan. The O Lau River has its river mouth at the utmost point in the north of Tam Giang lagoon. The Dai Giang (Cau Hai) River discharges into the Cau Hai lagoon at Cong Quan (Quan Sluice). Other two small rivers are Truoi River and Nong River that both discharge into the Cau Hai lagoon.

Therefore the flow of the rivers, especially flood flows, together with the effects of the tides will have an important role on the development of the lagoon and inlet system. It is necessary to take into account the flow of the rivers at the boundary of the lagoon.

Unfortunately, the flow observation stations are not located close to the river mouths, but quite far in the upstream. Water levels and flow discharges of the rivers are observed at three stations: Thuong Nhat station on the Ta Trach River (81 km far from the river mouth); Binh Dien on the Huu Trach River (41 km far from the river mouth); and Co Bi on the Bo River (37 km far from the river mouth). Currently, at Kim Long station on the Huong river (about 12 km from the river mouth) and Phu Oc station on the Bo River (about 28 km from the river mouth), only water levels are measured.

To estimate the flow discharge into the lagoon from each river, the model is necessary to be expanded to cover these locations so the flow data at these stations can be used for the boundary conditions of the model.

4.3.1. Monthly and annual flow

The observed monthly flows of the rivers and stations are shown in Table I.1 in Appendix I and Figure 4.6. The monthly river flows strongly vary between dry season and flood season.

- In the dry season from January to August, the total flow is less than 30% of the annual flow, the monthly flows are less than 0.5 times of yearly flow.
- In the flood season from September to December, the total flow is more than 70% of the annual flow, the monthly flows are from 1 to 4 times of yearly flow.

There are relationships of the flow discharges of the categories versus catchment area as shown in Figure I.11 in Appendix I. These relationships can be used for computation flow discharges of the seasons for the locations which have no observed data such as O Lau River, Cau Hai River and Truoi River.

On the Ta Trach River, there is a strong relationship of the observed flows in 1986 and 1987 at Duong Hoa and Thuong Nhat stations as can be seen in Figure I.12 in Appendix I. This relationship will be used for computation of the flow at Duong Hoa from observed discharge at Thuong Nhat.

The flow discharges of the flow seasons in Table 4.2 and Figure 4.7 will be used as the boundary conditions of the model to investigate long-term behaviour of the lagoon system in the normal condition of flow.

Table 4.2. River flow by season

Station	Basin area F (km ²)	Dry season (m ³ /s)	Flood season (m ³ /s)	Annual flow (m ³ /s)
Thuong Nhat (Ta Trach River)	208	6.9	33.5	15.7
Duong Hoa (Ta Trach River)	800	24.8	113	54.4
Binh Dien (Huu Trach River)	570	19.4	102	46.9
Co Bi (Bo River)	760	23.3	150	65.5
O Lau river	746	23.6	146	66.4
Truoi Reservoir	75.3	2.6	29.9	11.7
Truoi River	110	3.9	29.8	12.7
Cau Hai River	31	1.5	24.5	10.3

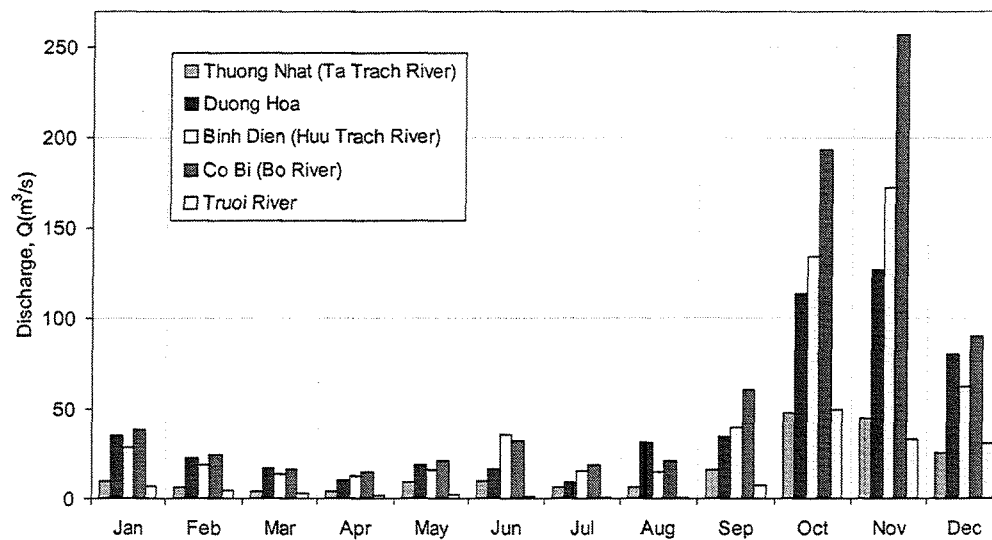


Figure 4.6. The observed monthly flows

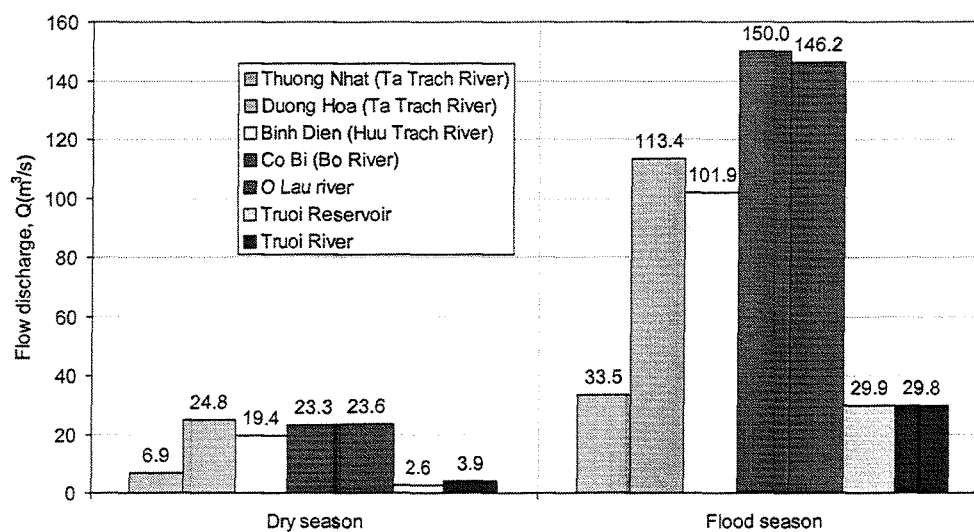


Figure 4.7. Distribution of river flow by season

4.3.2. Flood flow

Flooding and inundation cause many serious problems for the area. Extreme floods also deepen and widen inlet cross sections and may create breakthroughs the sand barrier to make new inlets. Hydraulic conditions of the system during extreme floods therefore are important to be considered.

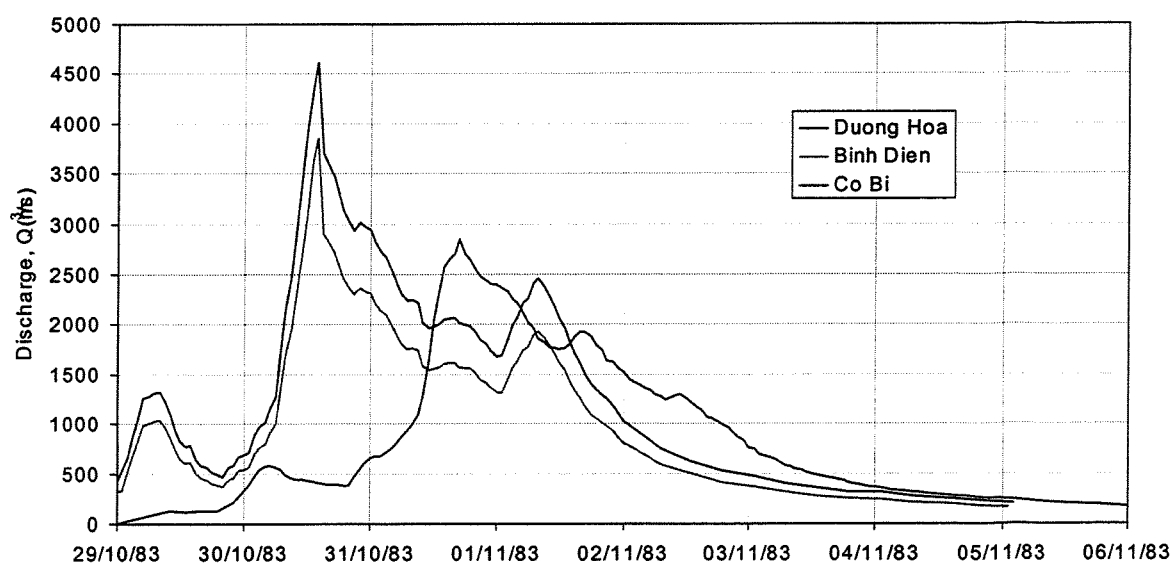


Figure 4.8. River discharges at gauging stations of the flood in October 1983

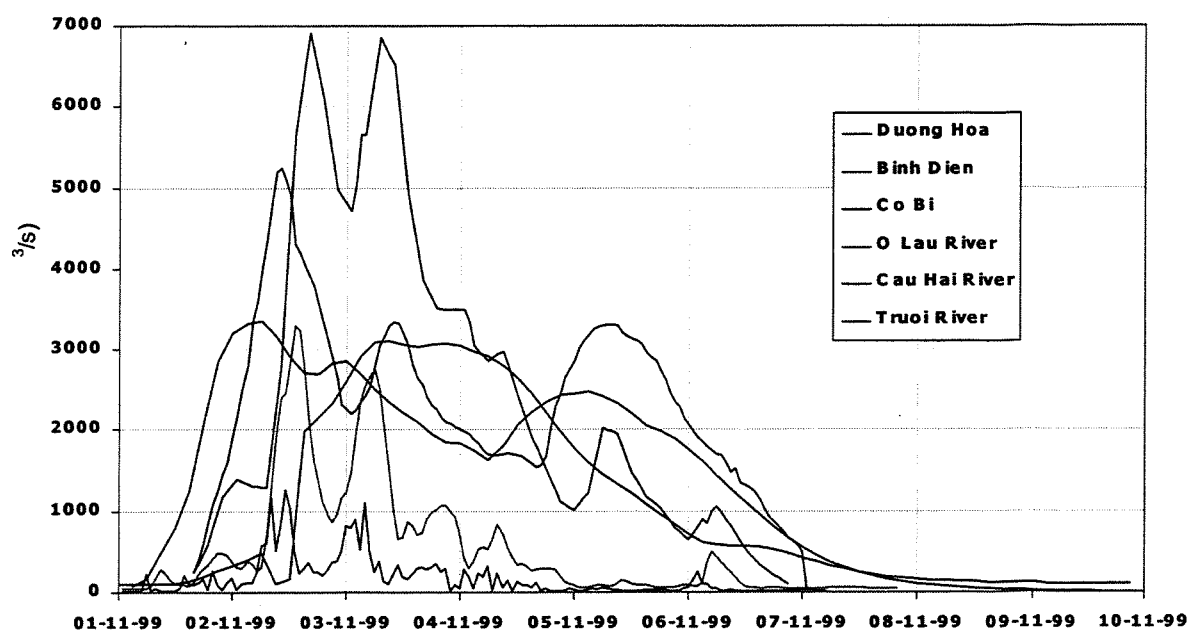


Figure 4.9. River discharges at gauging stations of the flood in November 1999

Floods are frequently occur every year in the area. But only flood data of 1983 and 1999 are available for this study.

According to Ngo Dinh Tuan *et al.*, 2001, these are big historical floods. The flood of October 1983 has recurrence probability of 8.1% at Duong Hoa ($Q_{\max} = 1250 \text{ m}^3/\text{s}$ at Thuong Nhat); 8.5% at Binh Dien ($Q_{\max} = 4020 \text{ m}^3/\text{s}$), 14% at Co Bi ($Q_{\max} = 2850 \text{ m}^3/\text{s}$) and 10% at Kim Long ($Z_{\max} = 4.88 \text{ m}$) (see Figure 4.8). The flood of November 1999 has its recurrence probability of 3% at Duong Hoa ($Q_{\max} = 6930 \text{ m}^3/\text{s}$); 3% at Binh Dien ($Q_{\max} = 5320 \text{ m}^3/\text{s}$), 10% at Co Bi ($Q_{\max} = 3420 \text{ m}^3/\text{s}$) and 1% at Kim Long ($Z_{\max} = 5.81 \text{ m}$) (see Figure 4.9).

During these floods, flood discharges at Thuong Nhat, Binh Dien, Co Bi and water levels at Kim Long and Phu Oc were recorded. Although there are some ambiguities of these data from difference sources, but these data are only that available for model calibration and verification in Chapter 5.

4.4. TOPOGRAPHIC DATA

4.4.1. River cross sections

The model is expanded to include the river network to simulate flow of the rivers discharging into the lagoon as mentioned in Section 4.3. Therefore, not only cross sections of the lagoon and inlets are required but also cross sections of the rivers are needed.

The cross sections of the rivers are based on the topographic data surveyed in 1986 by the Hydraulic Engineering Consultant Company No 1 (HEC1). The purpose of this survey was for the development of a hydraulic model in dry seasons with VRSAP. Therefore, the survey did not concern the flood plains and the obstructions during flooding (Nguyen Mai Dang, 1997).

For this study, the river cross sections are available only as the input data for the VRSAP model in the form of elevation – water surface width at fixed locations. This data are also suitable for DUFLOW and this is also a reason for the use of an existing schematisation of river network done for VRSAP to apply for DUFLOW.

4.4.2. Lagoon and inlet cross sections

The cross sections of the lagoon and inlets using in the model are based on a 1/50000-scaled bathymetry map measured using echo sounding by VIWRR in May 2000. The topographic map of the lagoon is shown in Figure I.15 in Appendix I

During the river flood event of November 1999, beside of the existing inlets are Thuan An and Tu Hien, a new inlet was opened at Hoa Duan. The Hoa Duan inlet then was closed in July 2000. The topography of the Thuan An and Hoa Duan inlets in May 2000 are shown in Figure I.14 in Appendix I.

The cross sections of the Thuan An inlet and Tu Hien inlet in 1993 are shown in Figure I.16 and Figure I.17 in Appendix I.

It is can be seen that geometry and cross sections of the inlets are changing with time under effects of waves, littoral drifts, tides and river floods. Therefore, effect of the inlet openings on the hydrodynamic characteristics of the system is necessary to be considered.

4.5. SEDIMENTARY DATA

4.5.1. Sediment transport in the rivers

In the province, there is no station for observation of sediment transport in the rivers. The sediment load and budget are roughly estimated as listed in Table 4.3 (Nguyen Duc Vu, 1995; VVA Project, 1996; Tran Dinh Hoi *et al.*, 2001).

Table 4.3. Annual river flow and sediment transport

River	Annual flow (10^6 m^3)	Sediment concentration (kg/m^3)	Sediment load (10^3 tons/year)
Huong River	5400	0.15	450
Bo River	1930	0.08	192
O Lau River	500	0.08	65
Dai Giang	500	0.07	35
Truoi River	372		27
Total from all rivers to the lagoon	6000		620

- Sediment sinks due to sand and gravel mining are estimated of $60\,000 \text{ m}^3/\text{year}$

4.5.2. Characteristic of sediment in the inlets and at the beach

Based on a geologic survey carried out by Vietnam Institute for Water Resources Research (VIWRR) in April 1999 at five bore-holes along the coast of Thua Thien-Hue province as shown in Figure I.18 in Appendix I, the top layer of soil is mainly medium to coarse sand up to the depth of 18m (Nguyen Khac Nghia *et al.*, 1999). The sediment is mainly quartz containing no carbonate. The solid density of the sediment is $\rho_s = 2650 \text{ kg/m}^3$. The dimension characteristics of sand in this layer are $d_{50} = 0.41\text{mm}$, $d_{90} = 1.40\text{mm}$ as seen in Figure I.19 in Appendix I. According to Shields (1936), the corresponding values of the critical Shields parameter is $\theta_{cr} = 0.032$ and the time-averaged critical bed shear stress is $\tau_{b,cr} = 0.210 \text{ N/m}^2$. The critical depth-averaged velocity is $u_{cr} = 0.35 \text{ m/s}$ to 0.40 m/s corresponding to the water depth of the inlets is from $h = 6 \text{ m}$ to 12 m .

According to Tran Dinh Hoi *et al.*, 2001, the sedimentary characteristics of the sand at the Thuan An inlet are $d_{50} = 0.39\text{mm}$, $d_{90} = 0.81\text{mm}$ as seen in Figure I.20 in Appendix I. The corresponding values of the critical Shields parameter is $\theta_{cr} = 0.032$ and the time-averaged critical bed shear stress is $\tau_{b,cr} = 0.204 \text{ N/m}^2$. The critical depth-averaged velocity is $u_{cr} = 0.37 \text{ m/s}$ to 0.41 m/s corresponding to the water depth of the inlets is from $h = 6 \text{ m}$ to 12 m .

4.5.3. Long-shore sediment transport

Longshore sediment transport is the most uncertain quantity. There are some calculations of this quantity for the Thua Thien-Hue coast, but the results are very different with the orders of hundreds percents.

At Thuan An and Hoa Duan inlets, according to the computation made by VIWRR (Nguyen Tuan Anh *et al.*, 1999) the long-shore sediment transports according to this calculation are $1.503 \times 10^6 \text{ m}^3/\text{year}$ north-westward and $0.063 \times 10^6 \text{ m}^3/\text{year}$ south-eastward. The net sediment transport is $1.440 \times 10^6 \text{ m}^3/\text{year}$ north-westward. The total transport is $1.566 \times 10^6 \text{ m}^3/\text{year}$.

This amount of sediment transport is in the order of $1.6 \times 10^6 \text{ m}^3/\text{year}$ that was estimated from survey of annual sediment budget, bottom topography changes and dredging studies as reported by Lee, 1970.

Tran Duc Thanh *et al.* (1996) calculated longshore sediment transport in the vicinity of the Thuan An inlet using CERC formula giving results of $1.41 \times 10^6 \text{ m}^3/\text{year}$ north-westward, $2.01 \times 10^6 \text{ m}^3/\text{year}$ south-eastward. Net sediment transport is $0.6 \times 10^6 \text{ m}^3/\text{year}$ south-eastward and the total sediment transport is $3.42 \times 10^6 \text{ m}^3/\text{year}$. This seems to be an exaggerated figure (VVA Project, 1996).

Tran Dinh Hoi *et al.* (2001) calculated sediment transport for the Thua Thien-Hue coast using SEDTRAN giving results of $0.11 \times 10^6 \text{ m}^3/\text{year}$ north-westward, $0.54 \times 10^6 \text{ m}^3/\text{year}$ south-eastward. Net sediment transport is $0.43 \times 10^6 \text{ m}^3/\text{year}$ south-eastward and the total sediment transport is $0.64 \times 10^6 \text{ m}^3/\text{year}$.

Tran Thanh Tung (2001) calculated sediment transport for the Thua Thien-Hue coast using UNIBEST with several transport formula and recommended the use of Van Rijn formula with a result for net sediment transport is $0.3 \times 10^6 \text{ m}^3/\text{year}$ north-westward to the Thuan An inlet and it is $0.1 \times 10^6 \text{ m}^3/\text{year}$ north-westward at Hoa Duan.

At the Tu Hien inlet, according to survey and estimated results made by Haiphong Institute of Oceanography (Tran Duc Thanh *et al.*, 1996) in 1993 and 1995, the long-shore sediment transport is $0.715 \times 10^6 \text{ m}^3/\text{year}$ south-eastward and it is $0.495 \times 10^6 \text{ m}^3/\text{year}$ north-westward. Net sediment transport is $0.220 \times 10^6 \text{ m}^3/\text{year}$ south-eastward. Total sediment transport is $1.210 \times 10^6 \text{ m}^3/\text{year}$.

From these results, the magnitudes of the total longshore sediment transport of $1.6 \times 10^6 \text{ m}^3/\text{year}$ in the vicinity of the Thuan An inlet and $1.2 \times 10^6 \text{ m}^3/\text{year}$ in the vicinity of the Tu Hien inlet seem to have a higher reliability than the others.

4.5.4. Sediment transport in the inlets

There were some observations of sediment transport in the inlets in 1993 and in the rainy season 1995 (Tran Duc Thanh *et al.*, 1996). These observations show that the sediment transport through the Thuan An inlet is 144 tons/day from the sea into the lagoon in the dry season and it is 2443 tons/day from the lagoon into the sea in the rainy season. The total sediment transport from the lagoon into the sea through the Thuan An inlet is about 259000

tons/year. This transport is 9500 tons/year through the Tu Hien inlet. The total sediment transports to the sea through both inlets are about 268000 tons/year. The observations also indicate that the bed load transport is about 17% percent of the total transport, i.e. 45000 tons/year.

4.6. CONCLUSIONS

- Because of there is not permanent gauging station for observation tidal water level in the sea in the area, tidal water levels at the inlets are computed using harmonic analysis method with harmonic constants determined from short time period of observed data. These computed values of tidal water levels are reasonable and will be used as the downstream boundary conditions of the model. The sensitivity of the harmonic constants, effects of storm surges and sea level rise on the model results will also be analysed after ward.
- To determine flows of the rivers discharge into the lagoon, the model needs to expand including the river network to cover the gauging stations that data are available for the upstream boundary conditions as well as check points for calibration and verification of the model.
- There is a strong variation of flow discharge into the lagoon between dry season and flood season. It is necessary to classify flow discharges of the rivers into categories to simulate the effects of the long-term conditions of normal flows and extreme conditions of flood flows to the lagoon and inlets.
- The available observed tidal data are too short for a tidal analysis. More observations of tidal water level at Thuan An and Tu Hien inlets are needed to be carried out with a standard period of continuous measurement (30 or 369 days). The fixed locations of measurement should be chosen so the water level is not effected by the flow from the rivers. The observations are also carried out during typhoons for storm surge analysis purpose.
- Flow data of the rivers discharge to the lagoon, especial the O Lau River need to be observed more. Observation of water level of the O Lau River is necessary to be done in a period of one year. Flow discharge is necessary to be observed in flood season from September to December.
- Observations of sediment transport from the rivers into the lagoon, sediment transport at the inlets are necessary to be done in both flood and dry seasons.
- Observations of the inlet cross sections are suggested to be done frequently, especially after each flood from upstream rivers.
- Measurement of coastline, beach profiles and sand dunes are also required to estimate long-shore sediment transports and its effect to the inlets. Topography of the inlets and vicinity areas are recommended for measurement frequently.
- For the purposes of agriculture and environmental management, it is necessary to observe and study density currents, salinity at the inlets, inside the lagoon and in the rivers.

Chapter 5. NUMERICAL MODEL OF THE LAGOON AND INLET SYSTEM

5.1. MODEL SCHEMATISATION

As mentioned in Chapter 4, because of lacking data in the lagoon area, the model of the lagoon and inlet system is necessary to expand including the river network. The model needs to cover the gauging stations that data are available for the upstream boundary conditions as well as checkpoints for calibration and verification of the model.

There are some 1D numerical models have been developed for the river system in the province, mainly for the purposes of flood control, drainage, and salt intrusion. But none of these models includes neither the lagoon nor the inlets. Basically, these models are developed one inheriting another using the same cross section data and for the same 1D model VRSAP computer software (see Nguyen Nhu Khue, 1991).

There is a schematisation of the river system in the province set up by Prof. Hoang Tu An for VRSAP in 1992 that is available for this study. This schematisation was primarily used in a drainage project for Hue City. The model and its schematisation are accepted suitable and are being used broadly for simulation the river system of the province (Nguyen Mai Dang, 1997). The schematisation includes all the main channels of Huong, Bo and Dai Giang rivers and the permanent gauging stations of Thuong Nhat, Binh Dien, Co Bi, Phu Oc and Kin Long. The lagoon, O Lau and Truoi rivers are not in this schematisation.

In this study this schematisation is chosen and expanded to the whole river network of the province including O Lau River, Truoi River, the Tam Giang-Cau Hai lagoon and the inlets. Therefore, the complete model of the river and lagoon system now can be used for routing river flows discharge into the lagoon. This model consists of

- 3 water level boundary points: Thuan An, Hoa Duan, Tu Hien. In some simulations without the opening of the Hoa Duan inlet, the boundary condition for this inlet is assigned to a zero flow discharge.
- 4 discharge boundary points: Duong Hoa (Ta Trach River), Binh Dien (Huu Trach River), Co Bi (Bo River), O Lau river
- Flow discharges of the Truoi River, Cau Hai River and other sub-basins are simulated in the model as discharge points.
- The checkpoints are Kim Long and Phu Oc stations where the water levels are available for model calibration and verification.
- The rainfall data inputted into the model is taken from recorded data at Hue station.

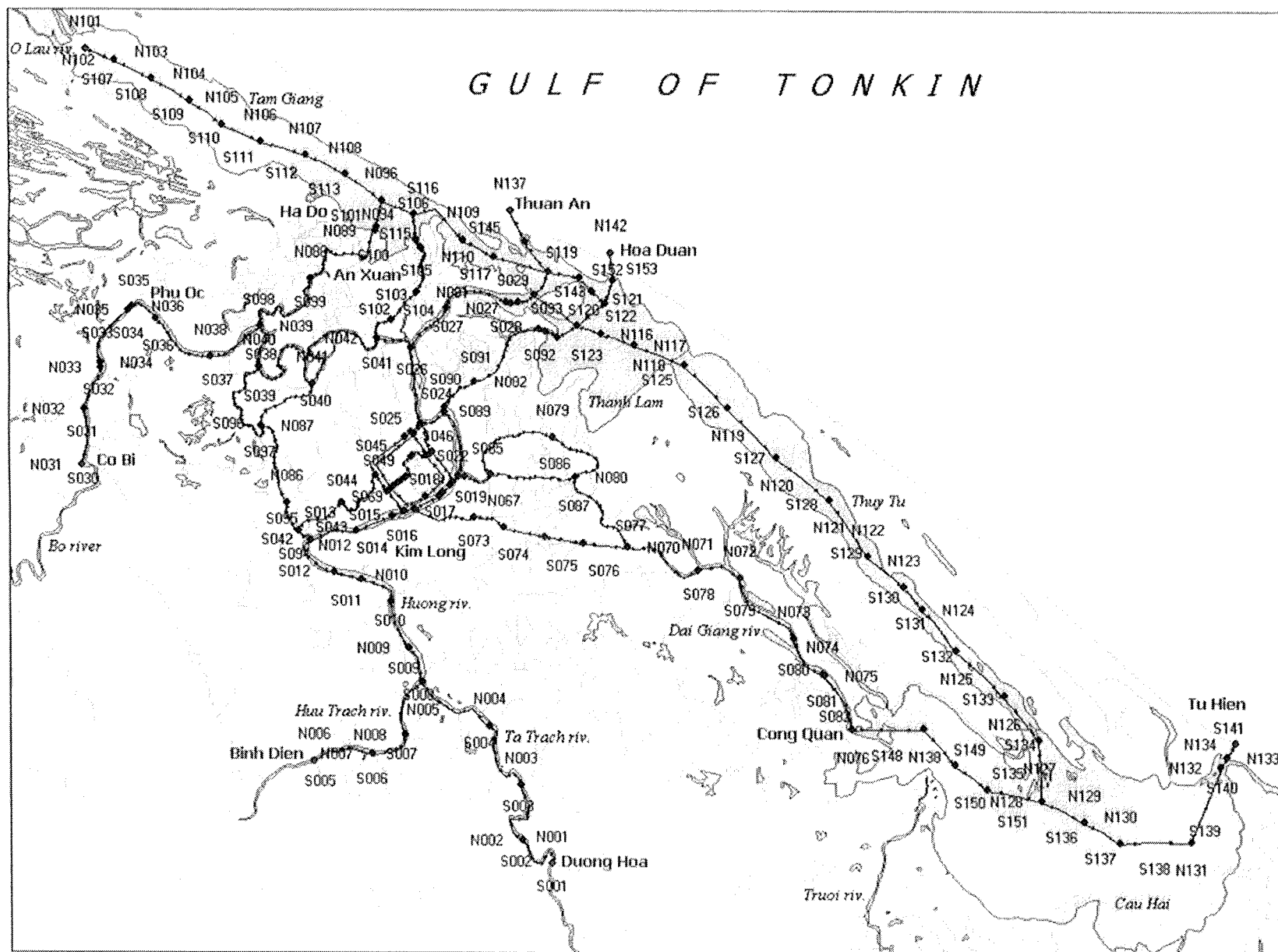


Figure 5.1. The schematisation of the river and lagoon system in Thua Thien-Hue province

5.2. BOUNDARY CONDITIONS

5.2.1. Down stream boundary conditions

The down stream boundary conditions of the model are the tidal water levels in the sea at the locations of the inlets. The water levels at the inlets are astronomic tides computed using the tidal constants determined as in Table 4.1 and Equation 4.1 as described in Chapter 4. Effects of tidal constants, storm surges and sea level rise will be considered in Chapter 6.

The distance from the Hoa Duan inlet to the Thuan An inlet is only 4 km so the sea water level at the Hoa Duan inlet can be taken the same at water level that predicted at Thuan An. While the distance from the Tu Hien inlet to the Thuan An inlet is about 40 km so the water level at this location is predicted using tidal parameters of the Tu Hien inlet.

5.2.2. Upstream boundary conditions

The upstream boundary conditions of the model are the flow discharges at Duong Hoa, Binh Dien and Co Bi. Flow discharges at Binh Dien and Co Bi are the observed data. Flow discharges at Duong Hoa are computed from observed data at Thuong Nhat station using hydrologic methods or regression.

5.2.3. Initial conditions

Initial conditions of flow discharge and water level are required at the first time step for every node of the model. If the model is stable, the errors in the initial conditions will decay and have no effect on the model results after several time steps. So that the initial conditions of the model can be chosen in such a way as to achieve the model stability. Also it is necessary to pay attention on effect of errors in the initial conditions on the model results. This can be done using the visualisation of the results such as using graphs or charts.

5.3. MODEL CALIBRATION

Model calibration is carried out to find the model parameters. The model parameters can be considered are channel roughness and others such as time steps, weighting factor θ . In the study, the different values of roughness, time step Δt , weighting parameter θ are investigated for sensitivity analysis. Some of these effect to the stability and accuracy of the model solution by effecting on the value of the Curant number Cr and the numerical dispersion E_{num} (see also IHE, 1995).

$$Cr = u \frac{\Delta t}{\Delta x} \quad (5.1)$$

$$E_{num} = \frac{u}{2}(1 - 2\theta)u\Delta t \quad (5.2)$$

The data available at the up stream boundaries (Duong Hoa, Binh Dien, Co Bi) and checking points at Kim Long and Phu Oc are only the data of the flood in October 1983 and the flood

in November 1999. The data of the flood in October 1983 is used for model calibration. The data of the flood in November 1999 will be used for model validation later.

At the checkpoints of Kim Long and Phu Oc stations, there are differences of observed water levels according to HMS and HEC1. These differences are due to the conversion from difference reference levels of observations to the standard HD Datum.

Because information on storm surge and cross sections of the inlets in 1983 are not available, effects of changing in sea water level, storm surges, and inlet openings will be considered.

5.3.1. Effect of the cross sectional topography and bottom roughness

The model calibration is carried out with firstly of the investigation on the channel bottom roughness. Different values of roughness are applied the same to all channel sections to find out the most suitable value. After that, different channel sections are fine turned with the variations of bottom roughness to get the best fit at the checkpoints.

Firstly, the cross sectional data are taken from those used in VRSAP model without taking account of flood plains. The bottom roughness that gives the best fit of computed and observed water level at check points is found very smooth, $K=70$ corresponding to Manning's roughness $n = 0.014$, where in VRSAP model this value is $n = 0.020$. This can be explained that in VRSAP model, there are storage areas acting as flood regulating functions of flood plains, where there is no regulating area in DUFLOW so floods have to flow in the channel as fast as they can to get the fitness of the model results with observed data. This can be solved with the addition of very large storage area in the cross sections.

After adopting very large storage areas for the cross sections by increasing storage widths at some certain levels based on the topography of the province, the bed roughness and model results obtained are more reasonable and suitable. The model results for various bed roughness are shown in Figure 5.2 and Figure 5.3, and Table II.4 in Appendix II.

Effects of bottom roughness to the water level at Kim Long station can be seen in Table II.4 in Appendix II and Figure 5.2. From this result, the water level at Kim Long strongly depends on the roughness. From Figure 5.2, the channel roughness in the range of $K=50$ to $K=60$ (corresponding to Manning's roughness coefficient $n = 0.020$ to 0.017 , respectively) can be found to be suitable for the model and can be applied for the channel sections.

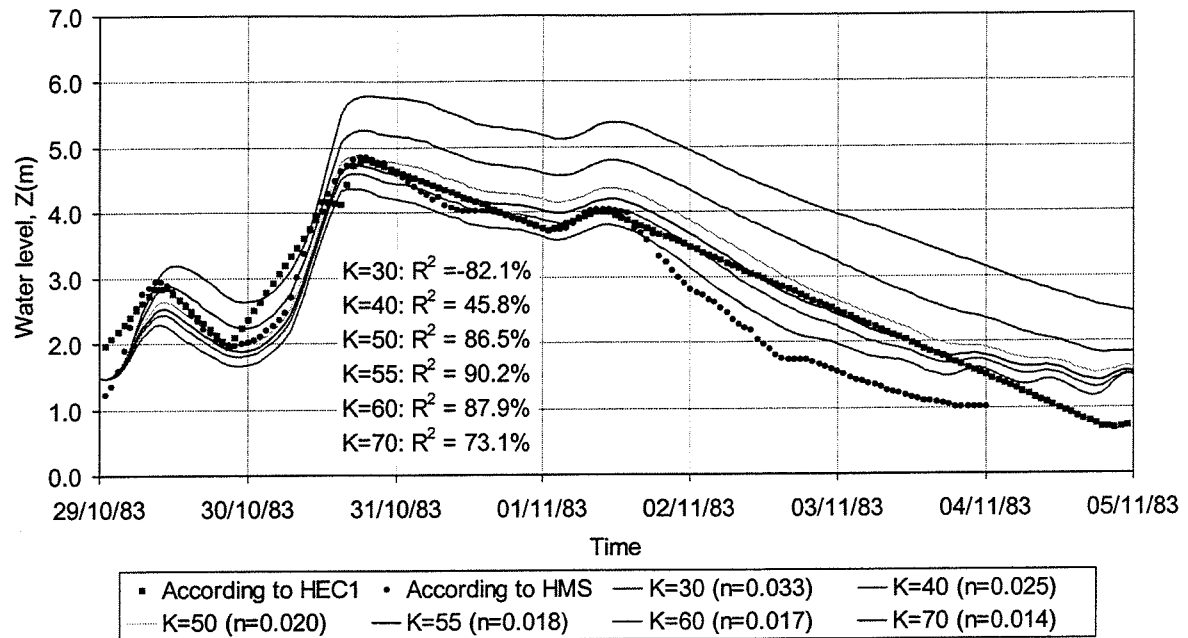


Figure 5.2. The variation of water level at Kim Long with different channel roughness

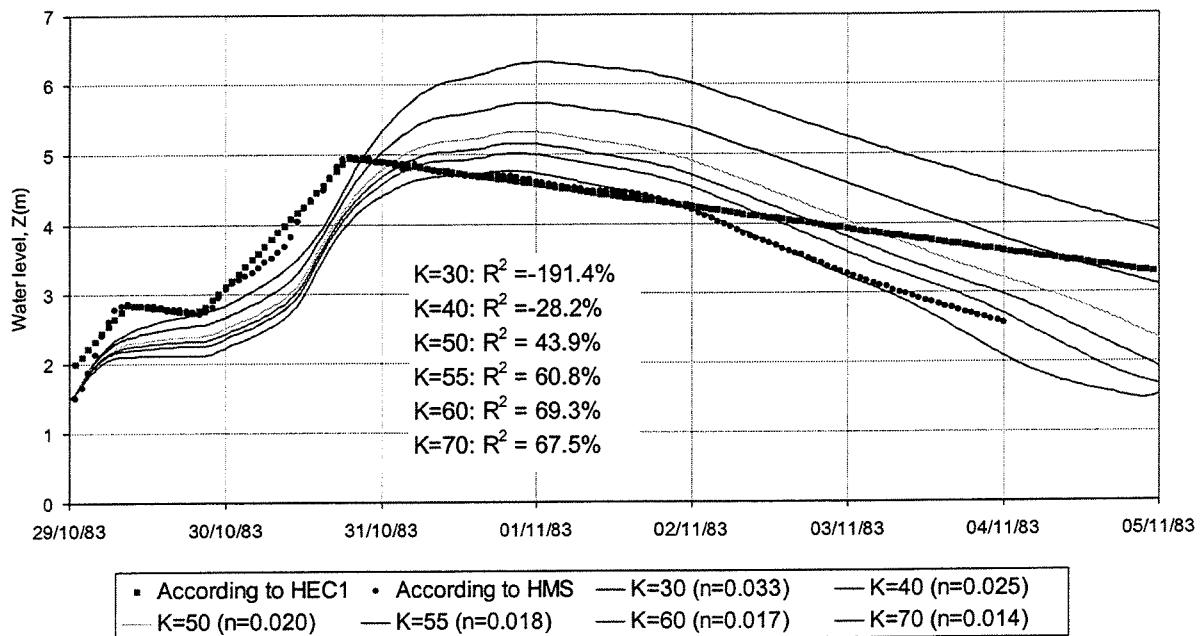


Figure 5.3. The variation of water level at Phu Oc with different channel roughness

5.3.2. Effect of the time step Δt

The time step has an important effect on the stability and the accuracy of the model solution. A smaller value of Δt will give a more accurate and stable solution.

Effects of the different time steps on the maximum computed water level at checkpoints can be seen in Figure 5.4, Figure 5.5 and Table II.5 in Appendix II. These results show that the variation of time steps do not effect so much to the model results and the time step Δt of 10 minutes is appropriate for the stability and the accuracy of the solutions.

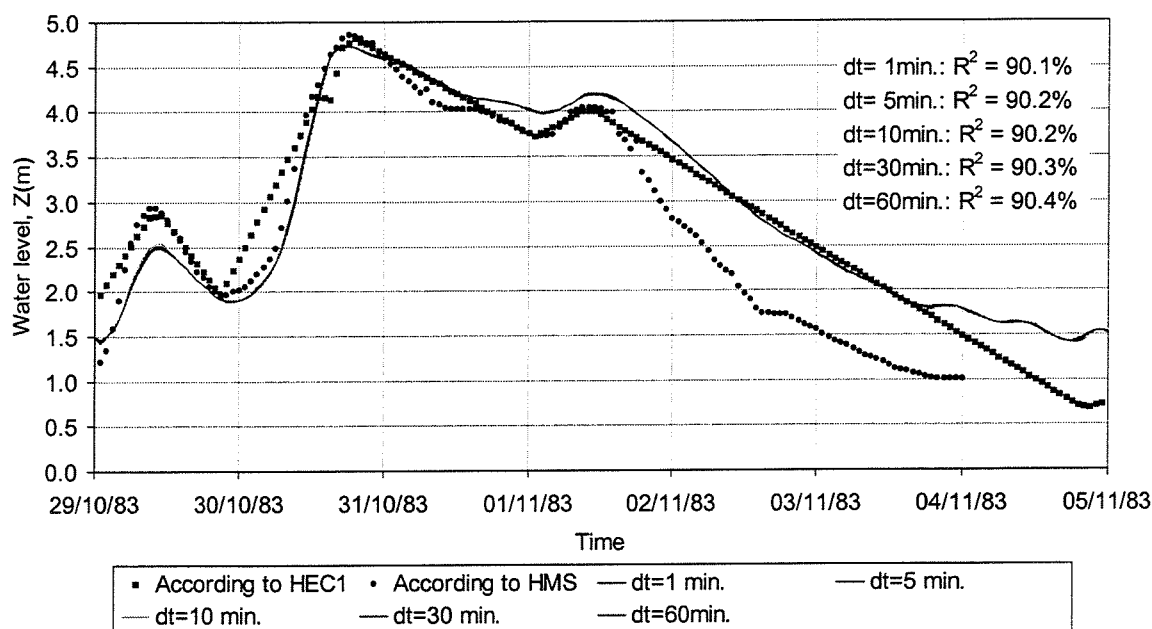


Figure 5.4. The variation of water level at Kim Long with different time steps

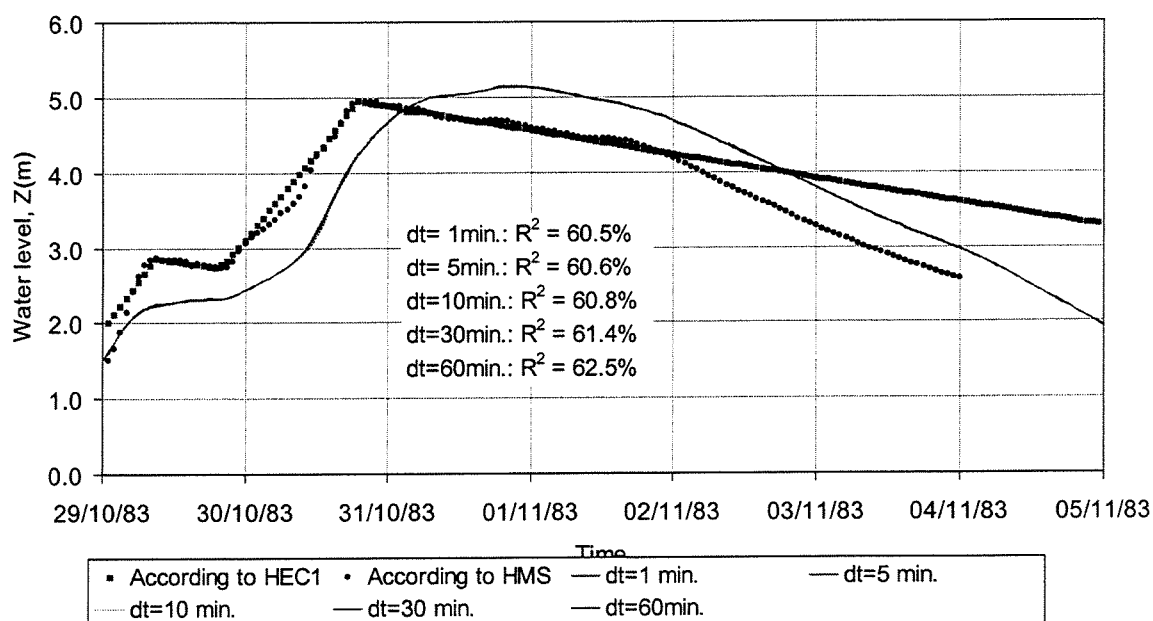


Figure 5.5. The variation of water level at Phu Oc with different time steps

5.3.3. Effect of the weighting factor θ

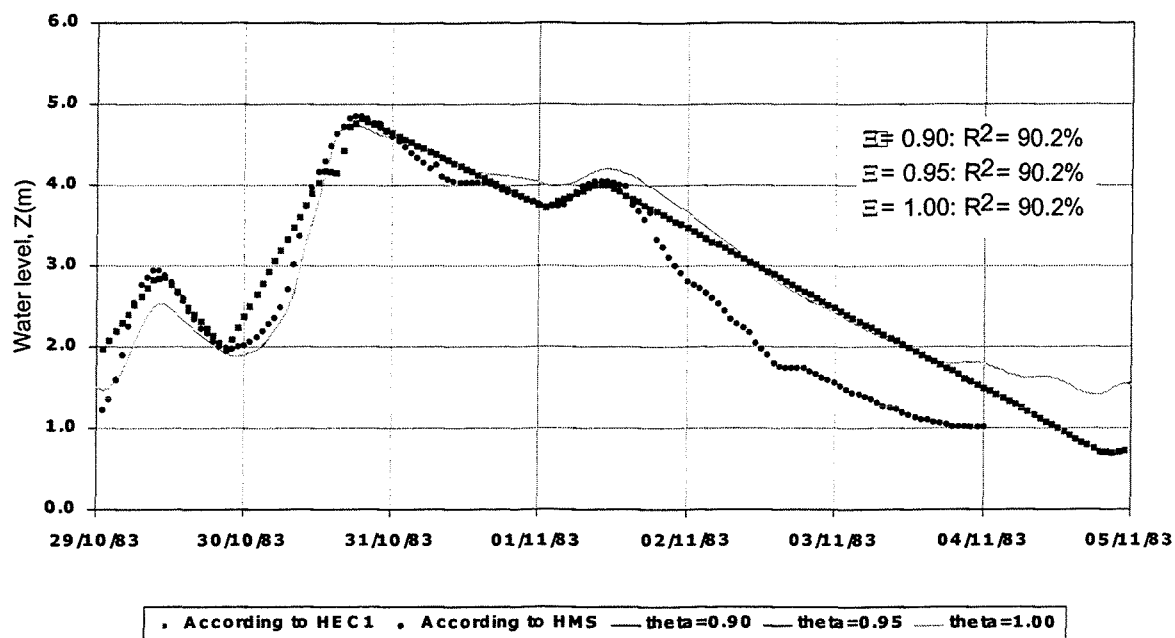


Figure 5.6. Effect of weighting factor θ on the water level at Kim Long

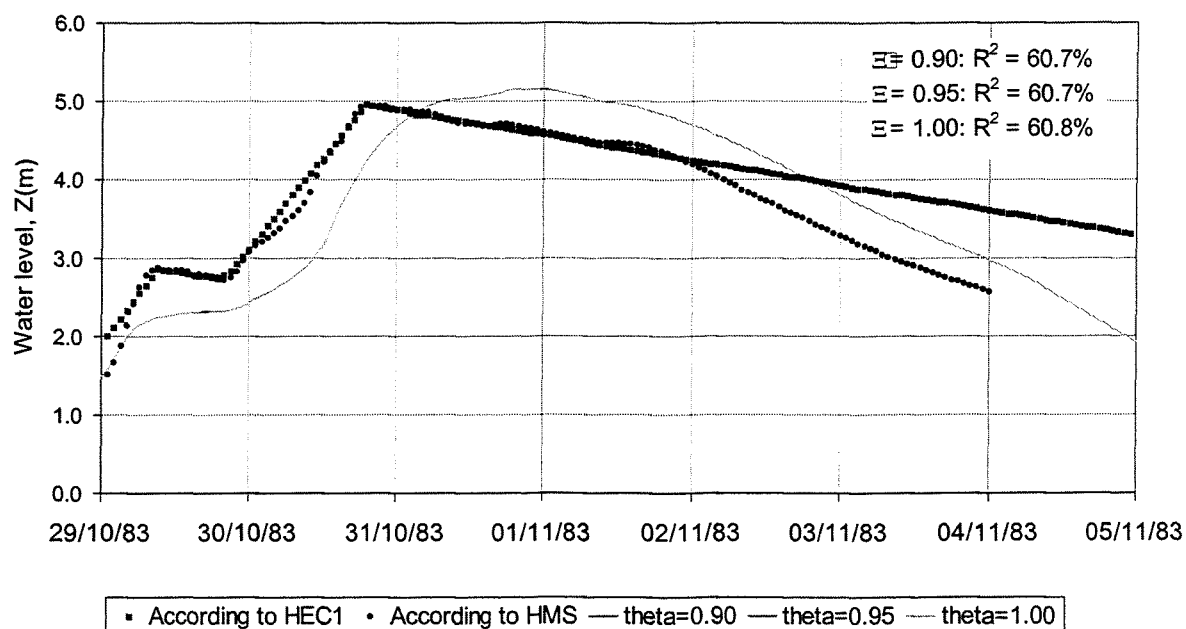


Figure 5.7. Effect of weighting factor θ on the water level at Phu Oc

The weighting factor θ controls numerical damping and also effects to the stability and the accuracy (numerical dispersion) of the solution. The value for theta may range from 0.5 to 1.

The low value of $\theta = 0.5$ gives the second order of the accuracy in time and space, i.e. it gives the results with the highest precision (because the numerical dispersion equals zero), but the calculation may become unstable. With the highest value of $\theta = 1$ the differential scheme becomes explicit with only first order accuracy.

In the model, changes of θ do not influence too much to the model result as can be seen in Figure 5.6, Figure 5.7 and Table II.6 in Appendix II. Therefore, the value of θ may be chosen in such a way that can achieve the model stability.

5.3.4. Effect of the storm surges and downstream water levels

Most of extreme floods in the province are caused by heavy typhoons. During a typhoon there may be a storm surge in the sea due to strong winds. A storm surge may effect to the flow in the rivers and lagoon. Therefor it is important to know how a change in sea water level or a storm surge does effect to the model result in a flood.

As can be seen in Figure 5.8, Figure 5.9 and Table II.7 in Appendix II, there are very little changes in water levels at Kim Long and Phu Oc during a flood in the cases of a storm surge less than 2m at the downstream boundaries in comparison with the non-storm surge condition (with mean water levels at Thuan An and Tu Hien are 1.15m and 1.07m, respectively) used for these boundaries. Effects of the sea water levels at the boundaries to the flood in the rivers are significance only if the changes in sea water levels are more than 2m. The reason for the small effect of storm surges on water levels at Kim Long and Phu Oc is the topographic condition. The locations of Kim Long and Phu Oc stations are far enough from the Huong river mouth for effects of storm surges.

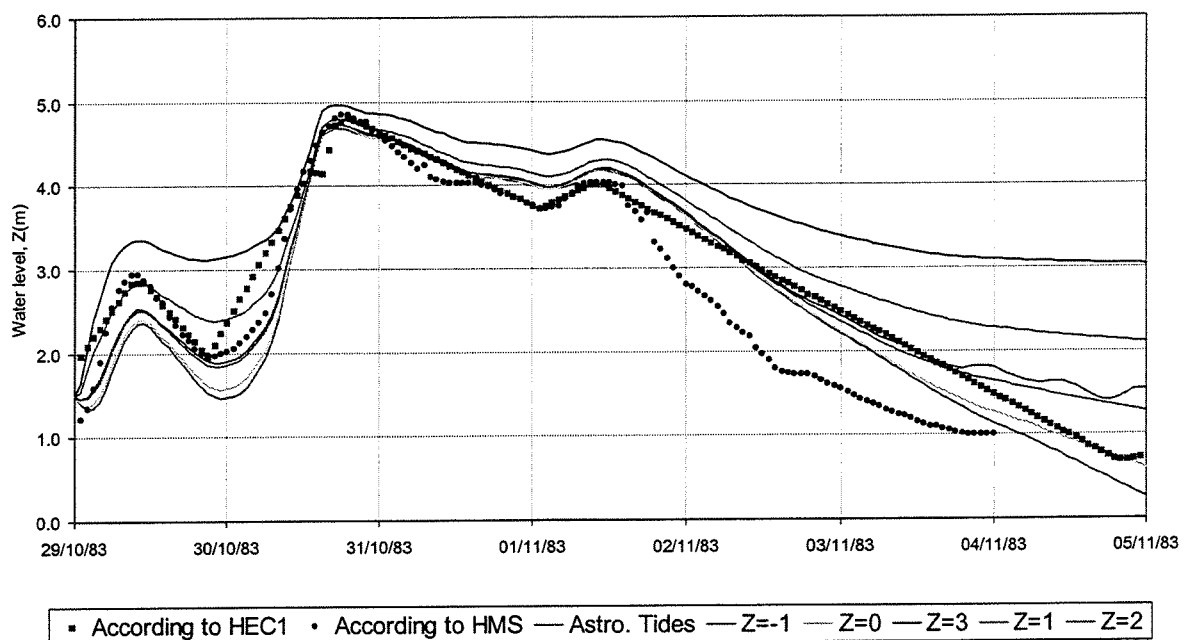


Figure 5.8. Effect of the sea water level on the water level at Kim Long in Flood 1983

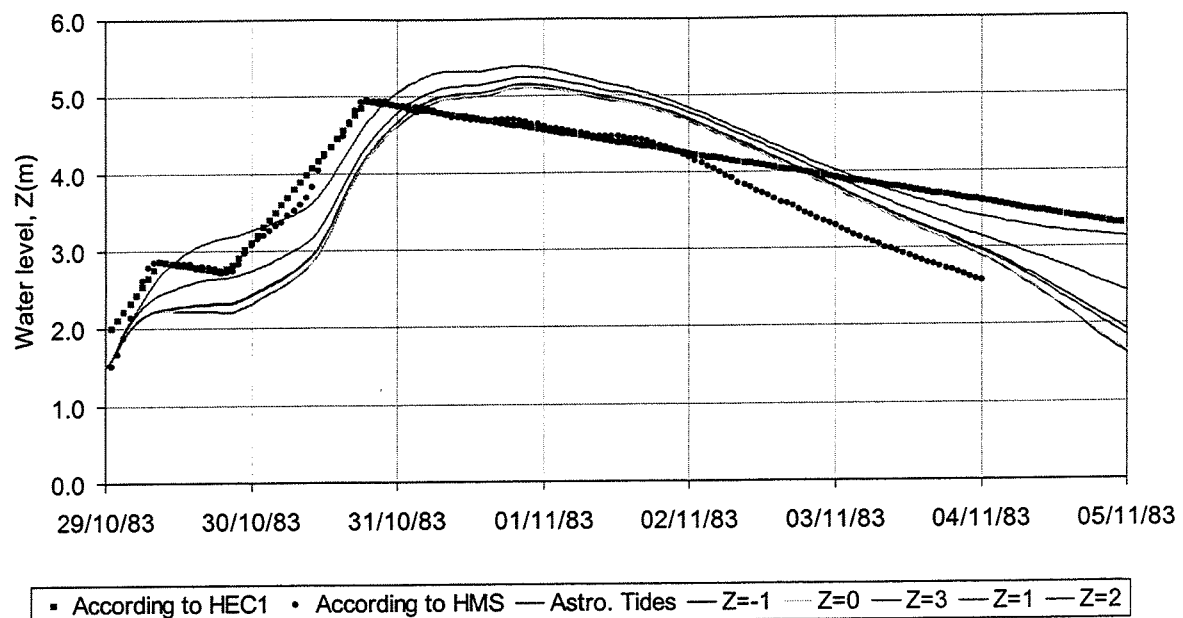


Figure 5.9. Effect of the sea water level on the water level at Phu Oc in Flood 1983

5.3.5. Effect of inlet openings

Because data of cross sections of the inlets in 1983 are not available, several possibilities of the inlet openings in 1983 are assumed as in Table 5.1. Effects of the uncertainty inlet openings to the model results are investigated. As can be seen in Figure 5.10 and Figure 5.11 and Table II.8 in Appendix II, change of inlet openings seem have no effect on the flood water levels at Kim Long and Phu Oc stations. This can be explained by the topographic condition of the rivers from the Huong river mouth to the locations of Kim Long and Phu Oc stations.

Table 5.1. List of the scenarios for inlet openings

Scenario ID	Thuan An inlet			Hoa Duan inlet			Tu Hien inlet		
	B(m)	d(m)	A(m ²)	B(m)	d(m)	A(m ²)	B(m)	d(m)	A(m ²)
SO02	535	12	4200	<i>closed</i>	<i>closed</i>	<i>closed</i>	189	6.5	826
SO09	535	12	4200	420	8	1868	697	1	510
SO10	535	12	4200	<i>closed</i>	<i>closed</i>	<i>closed</i>	697	1	510
SO11	344	6	1468	<i>closed</i>	<i>closed</i>	<i>closed</i>	697	1	510

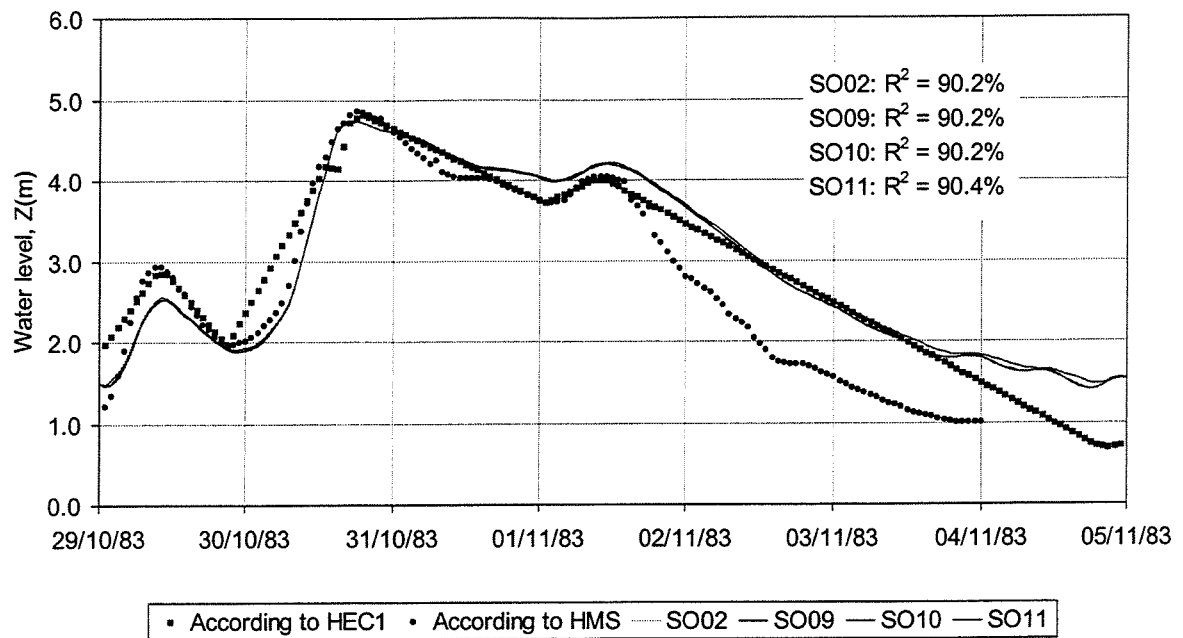


Figure 5.10. Effect of inlet openings on the water level at Kim Long in Flood 1983

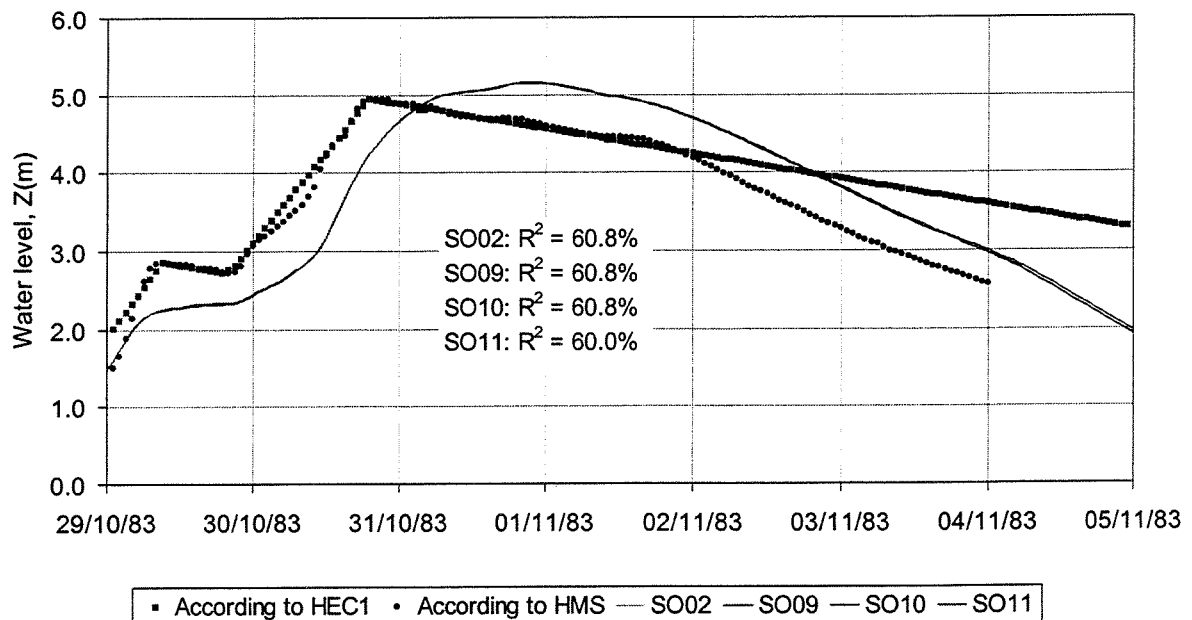


Figure 5.11. Effect of inlet openings on the water level at Phu Oc in Flood 1983

5.4. MODEL VERIFICATION

Model verification is required to check whether the model parameters are stationary and the topographic data is stable or not. If the model parameters determined in the calibration step are stationary and the topographic data is suitable, these can be used for the computation of scenarios in the future.

5.4.1. Model verification with the flood event of November 1999

The data of the flood in November 1999 is used for model verification. The flood of November 1999 was a historical flood with its recurrence probability of 3% at Duong Hoa ($Q_{\max} = 6930 \text{ m}^3/\text{s}$); 3% at Binh Dien ($Q_{\max} = 5320 \text{ m}^3/\text{s}$), 10% at Co Bi ($Q_{\max} = 3420 \text{ m}^3/\text{s}$) and 1% at Kim Long ($Z_{\max} = 5.81 \text{ m}$) according to Ngo Dinh Tuan *et al.*, 2001.

5.4.1.1. Effect of storm surges

Table 5.2. Effect of storm surges on the water level (m) at the inlets

Scenario	Value	Water level (m) at inlets			Difference in water level (m)		
		Thuan An	Hoa Duan	Tu Hien	Tam Giang – Cau Hai	Tam Giang – Thuan An	Cau Hai – Tu Hien
SZ01:Only astronomical tides	Max	0.89	0.90	1.29	0.34	0.94	0.29
	Min	0.36	0.38	0.90	-0.80	-0.09	-0.28
	Average	0.63	0.64	1.09	-0.08	0.37	-0.01
SZ02:Tides with mean WL=0	Max	0.32	0.31	0.32	0.83	1.25	0.53
	Min	-0.22	-0.21	-0.09	-0.53	-0.07	-0.11
	Average	0.05	0.06	0.10	0.28	0.54	0.21
SZ14:+Storm surge of 1.0m	Max	1.89	1.89	2.29	0.38	0.59	0.20
	Min	1.35	1.37	1.87	-0.73	-0.22	-0.73
	Average	1.62	1.63	2.07	-0.15	0.21	-0.09
SZ15:+Storm surge of 1.5m	Max	2.39	2.39	2.79	0.67	0.48	0.15
	Min	1.85	1.87	2.36	-0.69	-0.40	-1.11
	Average	2.11	2.12	2.57	-0.17	0.17	-0.12
SZ16:+Storm surge of 2.0m	Max	2.89	2.89	3.29	0.95	0.41	0.11
	Min	2.35	2.36	2.86	-0.64	-0.61	-1.50
	Average	2.61	2.62	3.06	-0.16	0.14	-0.15

During the flood of November 1999, there might be a storm surge due to strong wind. To see effects of sea water levels and storm surges on the model results, some scenarios of sea water level at boundaries are considered. A scenario of constant sea water level of 0m and scenarios of storm surges of 1m, 1.5m and 2m are investigated and compared with the boundary conditions of astronomic tides with mean water levels at Thuan An and Tu Hien are 0.59m and 1.09m, respectively. The results are shown in Figure 5.12, Figure II.1 to Figure II.3 and Table II.9 to Table II.11 in Appendix II.

From Figure 5.12, one can see that changes of the sea water level and storm surges have little effects on the flood water level at Kim Long.

Storm surges reduce flow velocities at the inlets some tens cm/s, especially during ebb tides. As can be seen in Table II.11 in Appendix II, storm surges reduce flood discharge through the Tu Hien inlet and cause increasing of flood discharges through the Thuan An and Hoa Duan inlets. This is due to the tidal range and mean water level at the Tu Hien inlet are higher than those at Thuan An area.

It can be seen in Table 5.2 that the maximum difference of water level in the lagoon and in the sea is about 1m.

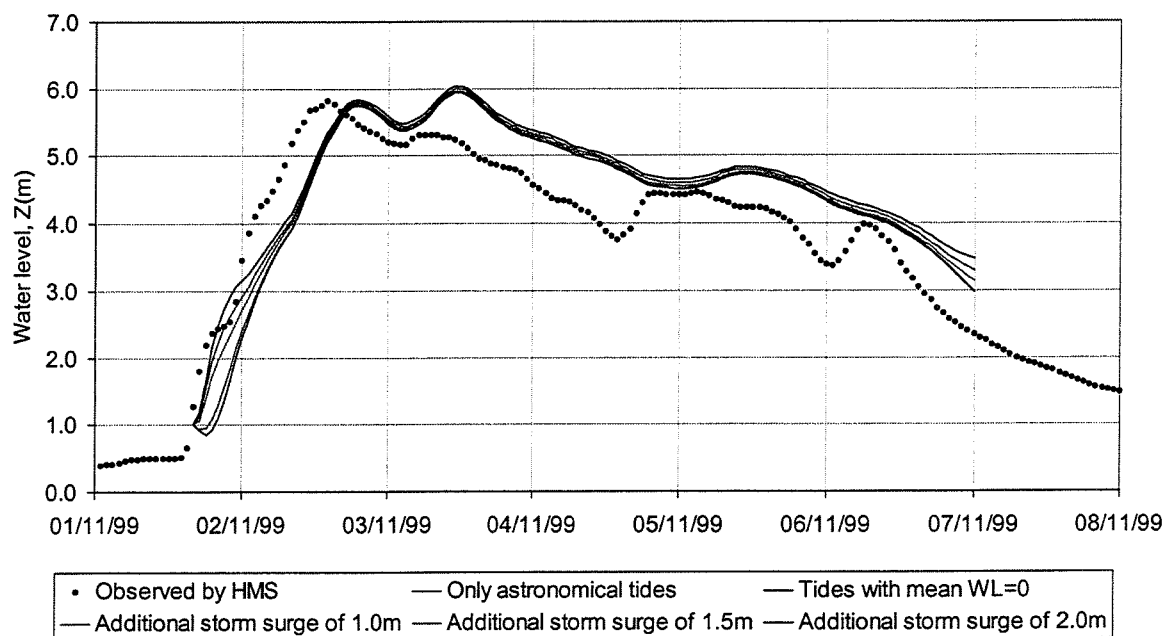


Figure 5.12. Effect of storm surges on the water level at Kim Long in Flood 1999

5.4.1.2. Effect of inlet openings

To consider effects of inlet openings to the model results, the following scenarios are chosen in computation as in Table 5.3:

- SO01: the cross sections of the Thuan An inlet and the Hoa Duan inlets in May 2000 (after the Flood of November 1999).
- SO07: the cross section of the Thuan An inlet in April 1999 with the opening of the Hoa Duan inlet of $B=420\text{m}$, $d=8\text{m}$.
- SO08: the cross section of the Thuan An inlet in April 1999 without the opening of the Hoa Duan inlet.

The results of the model as shown in Table 5.4, Table II.12 to Table II.14 and Figure II.4 to Figure II.6 in Appendix II. From these results, effects of inlet openings are mainly changing in flow velocities at the Thuan An and Hoa Duan inlets. Especially at the Thuan An inlets, the flow velocity may change very much and may be very high during high floods causing

erosion and deepening or widening the inlet as consequences. The openings of these inlets have little effects on the Tu Hien inlet (in both flow discharge and velocity) and have very little effect on the flood at Kim Long stations.

Table 5.3. List of the scenarios for inlet openings

Scenario ID	Thuan An inlet			Hoa Duan inlet			Tu Hien inlet		
	B(m)	d(m)	A(m ²)	B(m)	d(m)	A(m ²)	B(m)	d(m)	A(m ²)
SO01	535	12	4200	420	8	1868	189	6.5	826
SO07	405	11.5		420	8	1868	189	6.5	826
SO08	405	11.5		<i>closed</i>	<i>closed</i>	<i>closed</i>	189	6.5	826

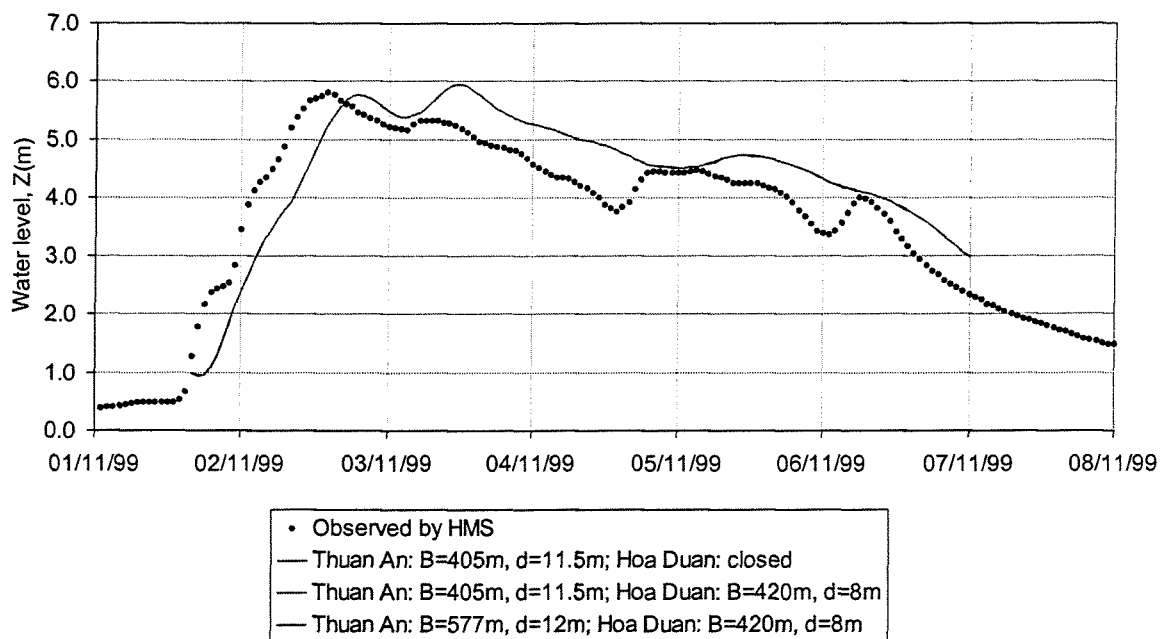


Figure 5.13. Effect of inlet openings on the water level at Kim Long during the Flood of November 1999

Table 5.4. Effect of inlet openings on the water level (m) at the inlets

Scenario	Value	Water level (m) at inlets			Difference in water level (m)		
		Thuan An	Hoa Duan	Tu Hien	Tam Giang – Cau Hai	Tam Giang – Thuan An	Cau Hai – Tu Hien
SO01: Thuan An: B=535m; Hoa Duan: B=420m	Max	0.89	0.90	1.29	0.34	0.94	0.29
	Min	0.36	0.38	0.90	-0.80	-0.09	-0.28
	Average	0.63	0.64	1.09	-0.08	0.37	-0.01
SO07: Thuan An: B=405m; Hoa Duan: B=420m	Max	0.89	0.90	1.29	0.36	0.97	0.29
	Min	0.36	0.38	0.90	-0.78	-0.08	-0.28
	Average	0.62	0.65	1.09	-0.07	0.39	-0.01
SO08: Thuan An: B=405m; Hoa Duan: closed	Max	0.92	1.21	1.30	0.38	1.04	0.31
	Min	0.38	0.53	0.92	-0.72	-0.07	-0.26
	Average	0.66	0.93	1.11	-0.03	0.45	0.03

5.4.2. Model verification with the flow in the dry season of 2000

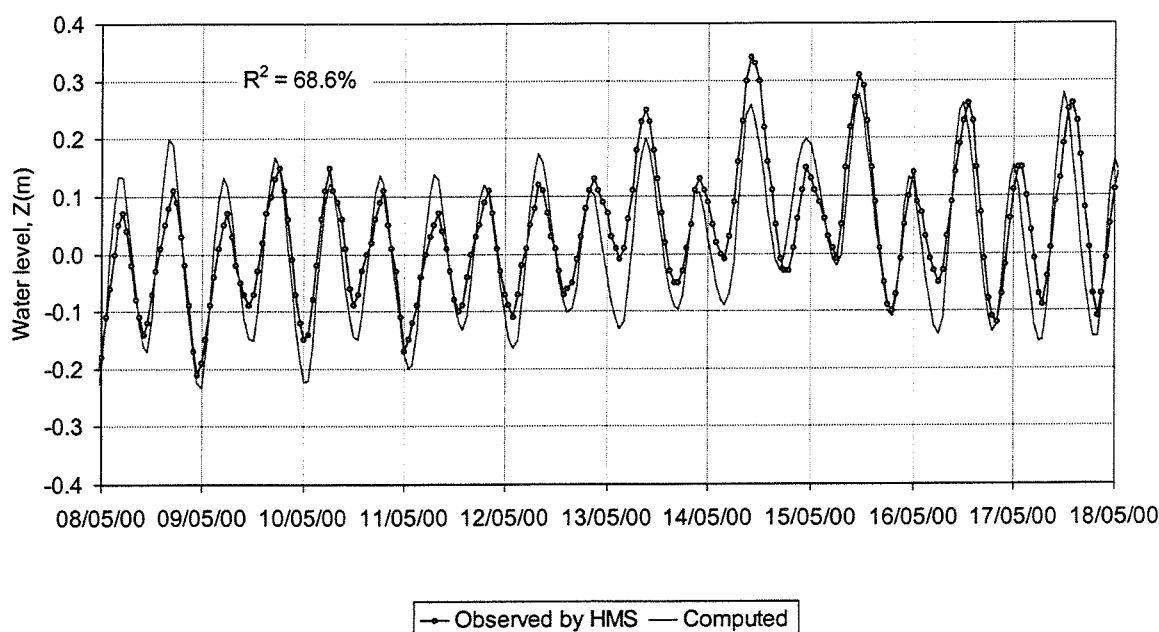


Figure 5.14. The computed vs. observed water level at Kim Long station in May 2000

The model is also verified for the dry season in May 2000 when observed water level at Kim Long is available. The flow discharges for upstream boundary conditions of the model are taken from the dry season from January to August, as mentioned in Chapter 4. The model result at Kim Long station is shown in Figure 5.14.

From this result, the model parameters that were determined in Section 5.3 (Model calibration) are also acceptable for simulation of flow in dry season in the system.

5.5. CONCLUSIONS

- The model has been calibrated and verified with only available data of the floods in 1983 and 1999. Some observed and computed data that were used as the model boundary conditions have a limited reliability. Other information such as storm surges and inlet openings are uncertainty. Sensitivity analysis of storm surges and inlet openings show that the uncertainties of storm surges and inlet openings only little effects on the flood at the checkpoints of Kim Long and Phu Oc stations.
- Storm surges reduce flow velocities at the inlets, especially during ebb tides.
- The openings of the Thuan An and Hoa Duan inlets have very little on the Tu Hien inlet.
- The maximum difference of water level in the lagoon and in the sea is about 1m at Thuan An and Hoa Duan locations during high floods. Therefore, the openings of these inlets are quite small and are still obstacles for flood evacuation. It is also the reason for little effects of storm surges and inlet openings on the flood in the rivers.
- Due to of high gradient of water surface profile in the Thuan An and Hoa Duan inlets, the flow velocities at these inlets are more than 2m/s, that are very high causing these inlets are widen and deepen during high floods. Together with erosion of the sand barrier due to storm surges, it is easy to have a breakthrough to make new openings at weak points of the sand barrier if overtopping occurs.
- The topographic data and the model parameters that were determined in Section 5.3 (Model calibration) can be acceptable for hydraulic simulation of the river network and lagoon system. In the following chapter (Chapter 6), the topographic data and the model parameters will be used for computation and analysis the hydraulic conditions of the lagoon and tidal inlet system.

Chapter 6. HYDRAULIC CHARACTERISTICS AND INLET STABILITY ANALYSIS

In this chapter, hydraulic characteristics of the lagoon and tidal inlets are investigated. Flow velocity, tidal prism as well as water level and flow discharge are computed with the model parameters that were determined in Chapter 5 with different scenarios of sea water levels and inlet openings.

The computations are done for a normal condition of river flow in a dry season and extreme situations of floods. In the dry season, effect of tidal parameters determined in Chapter 4, sea level rise and the closure of the Hoa Duan inlet are taken into the consideration. The extreme flood of November 1999 with different scenarios of storm surges and inlet openings are considered.

6.1. THE HYDRAULIC CHARACTERISTICS OF THE SYSTEM IN DRY SEASON

6.1.1. Hydraulic characteristics of the lagoon and inlets

To get acquainted with the hydraulic characteristics of the lagoon and inlets in dry season that is lasting 8 months from January to August, the computation is done representatively for May 2000 when some observations are available for checking. The upstream boundary conditions are taken from averaged river flows of this season as mentioned in Chapter 4. The downstream boundary conditions of sea water level are the tidal water level produced for May 2000. At this time, the Hoa Duan inlet was still opened since the flood of November 1999. The inaccuracy of the tidal parameters, sea water level and inlet openings will be considered in next sections consequently.

The computation results are shown in Table 6.1 and Table 6.4, Table II.15 to Table II.18 and Figure II.7 to Figure II.9 in Appendix II with the run number SZ01 (scenario SZ01). From these results, the characteristics of the system in the dry season can be summarised as follows:

6.1.1.1. Tidal prism

Base on the model results, the tidal prism is computed using

$$P = \int_0^{T_{flood}} Q(t) dt \approx \sum_{i=1}^n \bar{Q}_i \Delta t_i \quad (6.1)$$

The tidal prisms of the inlets are arranged in Table 6.1.

The computed value of the tidal prism at the Thuan An inlet is $P = 32 \times 10^6 \text{m}^3$, is approximately equivalent to the value of $P = 36 \times 10^6 \text{m}^3$ determined from observed data in May 2000 by VIWRR (Tran Dinh Hoi *et al.*, 2000) and the value of $P = 31 \times 10^6 \text{m}^3$ observed in March 1993 (Nguyen Tuan Anh *et al.*, 1999). The difference between the computed value and these observed values are 11% and 3%, respectively. The computed and observed values of the tidal prism at the Hoa Duan inlet are $P = 16 \times 10^6 \text{m}^3$ and $P = 21 \times 10^6 \text{m}^3$, respectively (the difference is 24%). The computed the tidal prism at the Tu Hien inlet is $P = 12 \times 10^6 \text{m}^3$. The observed value of the tidal prism in the Cau Hai lagoon in March 1993 is $P = 8 \times 10^6 \text{m}^3$

(Nguyen Tuan Anh *et al.*, 1999). The geometry of the inlets in 2000 may be very different with those in 1993. This leads to the differences in tidal prisms of 1993 and 2000.

The total tidal prism of the lagoon is about $P = 57 \times 10^6 \text{ m}^3$ (see Table 6.3). This value is less than the total values of tidal prisms in the three inlets of Thuan An, Hoa Duan and Tu Hien. The reason for this difference is the phase lag of the tides between these inlets.

The tidal prisms of the inlets strongly relate with the maximum flow discharges as can be seen in Figure 6.1. From this relationship, the value of $C_K = 0.895$ is found for the Equation 3.5 $P = Q_{\max} T / \pi C_K$ in Chapter 3. This equation can be used for estimating tidal prisms of the inlets approximately.

Table 6.1. Spring tidal prisms of the inlets

Inlet	Tidal prism $P (10^6 \text{ m}^3)$	Maximum discharge $Q_{\max} (\text{m}^3/\text{s})$	Cross sectional area $A (\text{m}^2)$	Source
Thuan An	32	2400	4200	Computed by DUFLOW model
	36	2660	6400 (*)	Observed by VIWRR, May 2000
	31			Observed 1993
	47	2900	2900	According to Lee, 1970
Hoa Duan	16	1170	1870	Computed by DUFLOW model
	21	1670	2250 (*)	Observed by VIWRR, May 2000
Tu Hien	12	718	826	Computed by DUFLOW model
	8			Observed 1993

Note: (*) These values of cross sectional areas were not measured at the minimum sections of the inlets.

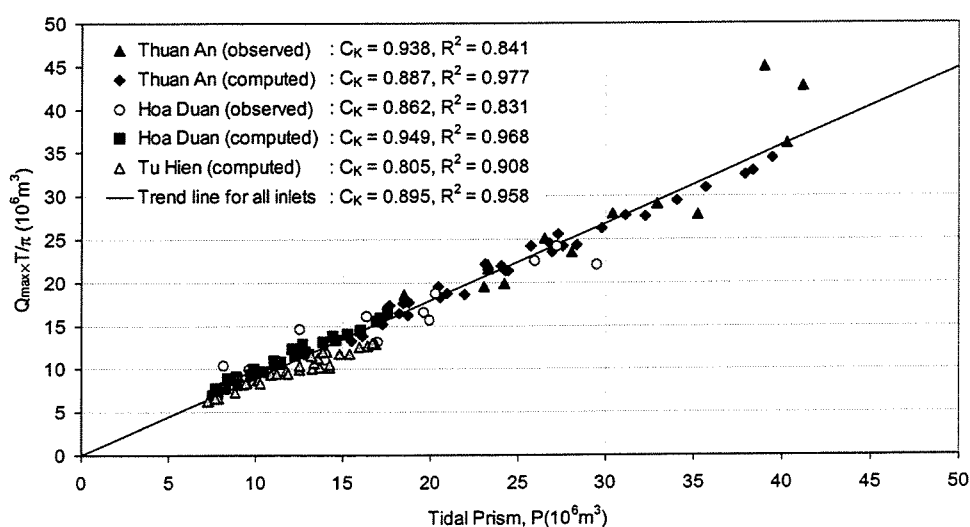


Figure 6.1. The relationship between tidal prism P and $\frac{Q_{\max} T}{\pi}$

6.1.1.2. Flow velocity

The maximum flow velocities of flood and ebb tides at Thuan An and Hoa Duan are about 0.6 m/s and are quite symmetric. These values are equal to the observed values in March 2000 reported by Tran Dinh Hoi *et al.* (2001). The observed values of the maximum flow velocities of flood and ebb tides at the Thuan An inlet made by VIWRR in May 2000 are 0.41 m/s and 0.50 m/s, respectively. These observed values at the Hoa Duan inlet are 0.74 m/s and 0.70 m/s, respectively. The observed values at the Thuan An inlet are smaller than the computed values because the locations of the observations were not located at the gorge section (i.e., the minimum area cross section) of the inlet. So in case both of these inlets are opened, the maximum velocities at Thuan An and Hoa Duan are quite small. It means that the sediment flushing capacities of these inlets are small. These inlets are not able to flush the sediment out to maintain their channel. Therefore, they will shoal and will be narrowed. If one of these inlets is closed, the maximum velocity at the other will increase to the order of 1 m/s as can be seen in Section 6.1.4. This order of flow velocity is suitable for sediment flushing and maintenance of an inlet.

The maximum flow velocities at the Tu Hien inlet are 0.84 m/s at flood tide and 1.09 m/s at ebb tide. These values are appropriate for sediment flushing. From the model results, it can be seen that flow velocity in the Tu Hien inlet is asymmetric. The maximum ebb velocity is higher the maximum flood velocity a magnitude of 0.2 m/s.

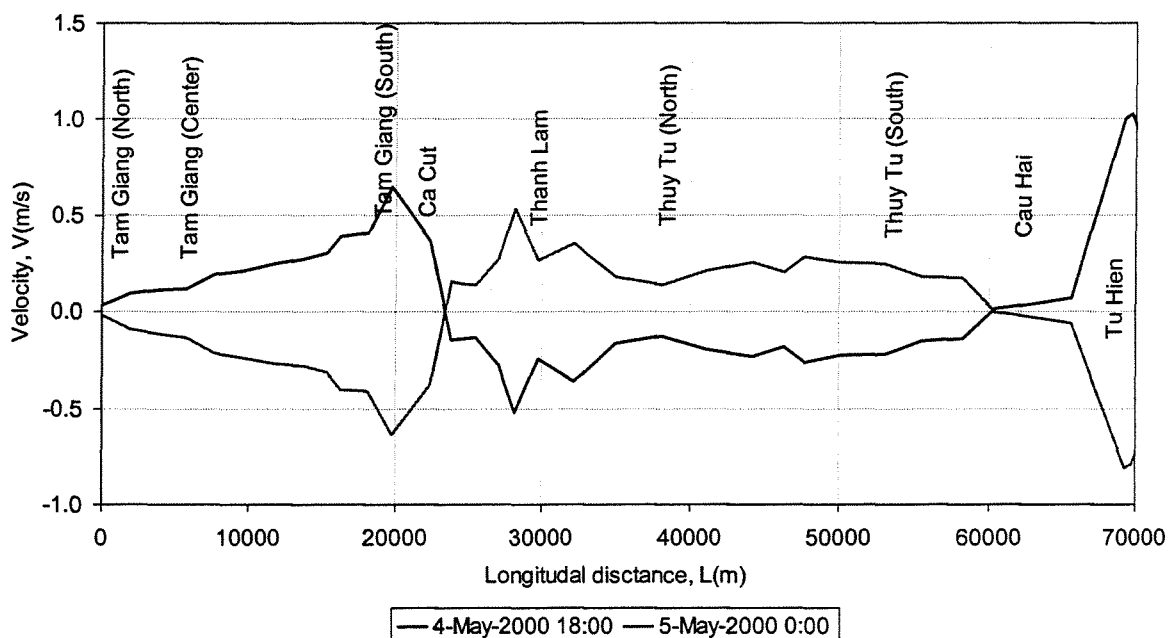


Figure 6.2. Distribution of flow velocity in the Tam Giang-Cau Hai lagoon in the dry season

As be shown in Figure 6.2 and Table II.15 in Appendix II, the maximum flow velocity in the Tam Giang lagoon increases from 0.03 m/s in the north to 0.2 m/s at the middle and to 0.65 – 0.75 m/s as close to the Thuan An inlet. The velocity in the Thanh Lam lagoon is about 0.25 – 0.30 m/s maximum. In the Thuy Tu lagoon, it is about 0.15 m/s in the northern part and 0.18 –

0.27 m/s at the southern end. The maximum flow velocity in the Cau Hai lagoon is about 0.07 – 0.08 m/s.

The increments of the flow velocities in the lagoon as close to the Thuan An and Hoa Duan inlets can be improved by the increment of the depth of the ebb tidal channel in the lagoon as can be seen in Figure 4.11 and Figure 4.12 in Chapter 4.

The flow velocities in the northern part of the Tam Giang lagoon and in the Cau Hai lagoon are less than 0.1 m/s. This value may be too small for flow circulation in these areas and may be an auspicious condition for sedimentation of these lagoons.

6.1.1.3. *Flow discharge*

The maximum flow discharges during flood tide and ebb tide at the Thuan An inlet are 2400 m³/s and 2330 m³/s, respectively in case the Hoa Duan inlet is opened. The observed values made by VIWRR in May 2000 are 2660 m³/s during flood tide and 3180 m³/s during ebb tide. If the Hoa Duan is closed, the maximum discharges at the Thuan An inlet will increase to 3300 m³/s during flood tide and 3250 m³/s during ebb tide. These values are close to the observed value of 2900 m³/s as reported by Lee (1970).

The maximum flow discharges during flood tide and ebb tide in May 2000 at the Hoa Duan inlet are 1170 m³/s and 1120 m³/s, respectively. The observed values are 1670 m³/s and 1510 m³/s, respectively.

The computed discharges of these inlets are smaller than the observed values. This may be caused by the changes of the inlet cross sections.

The maximum flow discharges during flood tide and ebb tide at the Tu Hien inlet are 720 m³/s and 860 m³/s, respectively.

The averaged distributions of the flow in the dry season in the Thuan An, Hoa Duan and Tu Hien inlets are 54%, 26% and 20%, respectively. When the Hoa Duan inlet is closed, the flow is redistributed as 74% to the Thuan An inlet and 26% to the Tu Hien inlet.

Because of the observed data of river flows for the upstream boundary conditions of the model in May 2000 are not available, the averaged values of the river flows are used for these boundaries instead of observed data. This may leads to the differences in observed and computed flow discharges in the inlets. Therefore, to see the errors made to the model results by using averaged values of the river flows in the dry season, the changes of $\pm 20\%$ and $\pm 50\%$ of the averaged river flows are added to the model boundary conditions. The model results show that, changes of 50% of the averaged river flows on the model boundary conditions cause only 2% changing in computed tidal prisms. This effect is minor because in the dry season, the inlets convey to the sea every day an mean water volume of $8.34 \times 10^6 \text{ m}^3/\text{day}$ or $4.17 \times 10^6 \text{ m}^3/\text{semi-durnal tidal cycle}$. That is only 7% of the total water volume exchanged between the lagoon and the sea in one semidiurnal tidal cycle. Hence, effect of the use of averaged river flows causes an error of only 2% of computed tidal prisms.

From this result, we can conclude that the main forces acting on hydrodynamics of the system in the dry season are tides. Effects of river flows in the dry season to hydrodynamics of the

system are small. The averaged values of river flows in the dry season can be used for model boundary conditions without significant effects.

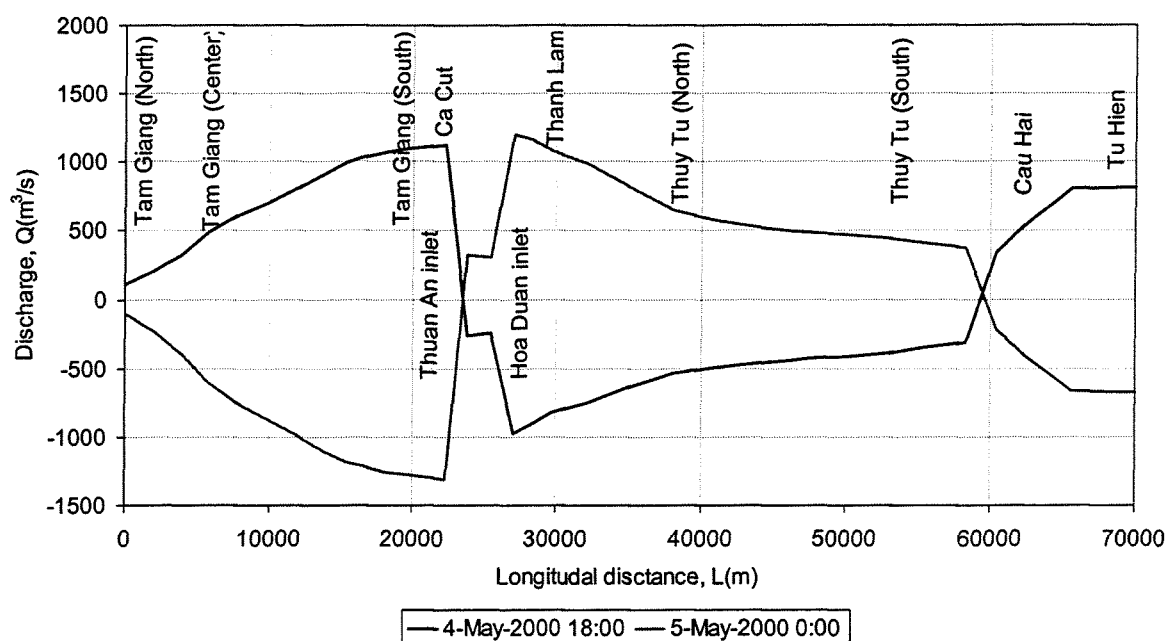


Figure 6.3. Flow discharge along the lagoons on 4/5/2000

6.1.1.4. Water level and tidal range

The maximum difference in water level between the Tam Giang lagoon and the Cau Hai lagoon is 0.18 - 0.26 m. The difference in water level between the Tam Giang lagoon and the Thuan An inlet is about 0.25 - 0.27 m maximum, between the Cau Hai lagoon and the Tu Hien inlet is 0.14 - 0.20 m maximum.

The tidal range in the Tam Giang lagoon is about 0.60m. The tidal range decrease gradually from the Thuan An inlet to the Thuy Tu lagoon. It is 0.64m at Thuan An, 0.61m at Kim Long, 0.56m at Thanh Lam, 0.41m at north Thuy Tu, and 0.26m at south Thuy Tu. The tidal range in the Cau Hai lagoon is 0.21 m. Where the tidal in the Tu Hien inlet is 0.28m with the data of May 2000.

Model results show that the time difference of HW between the Thuan An inlet and the northern end of the Tam Giang lagoon is about 2 hours, and the time difference of HW between the Thuan An inlet and the southern end of the Thuy Tu lagoon is about 3 hours. These results are suitable with the propagation of tidal waves in the lagoons with an average depth of 1.5 m.

Due to the obstruction of the ebb tidal delta at the southern end of the Thuy Tu lagoon, the tides that enter the lagoon via the Thuan An inlet and the Tu Hien inlet have a meeting-point at this place (the location at about 66 km in Figure 6.4 and Figure 6.5). This is also the relative separation of the Tam Giang-Thanh Lam-Ha Trung-Thuy Tu lagoons and the Cau Hai lagoon.

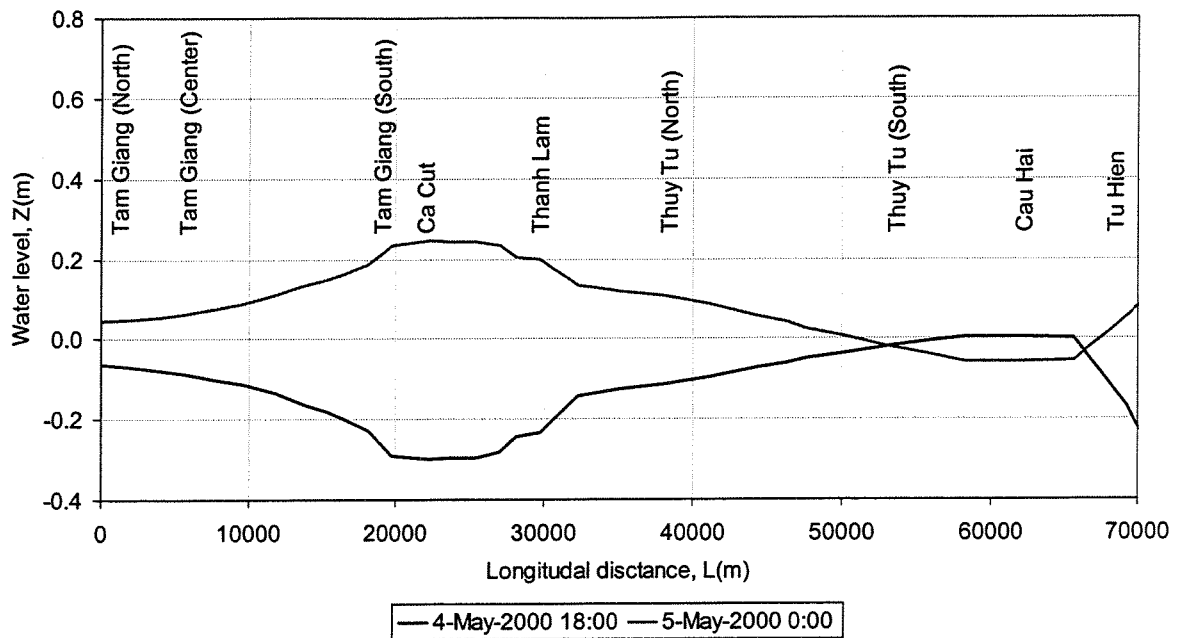


Figure 6.4. The water profile in the Tam Giang-Cau Hai lagoon in the dry season

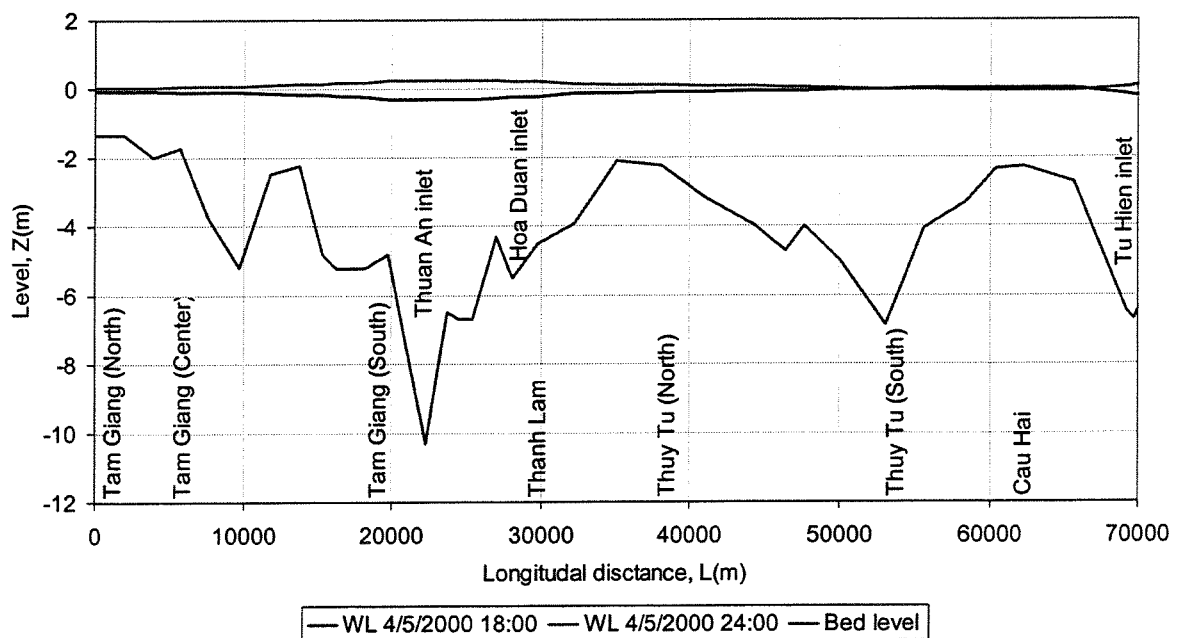


Figure 6.5. Water depth along the Tam Giang-Cau Hai lagoon in the dry season

6.1.2. Effects of the M_2 tidal parameter

The objective of this section is to consider the sensitivity of the tidal parameters that were determined in Chapter 4 with respect to the model results.

As can be seen in Table 4.1 (Section Tidal water level, Chapter 4), M_2 is one of the most important tidal constituents. Therefore, the tidal amplitude $H(M_2)$ of the M_2 tidal constituent is chosen for investigation of effects of the errors in tidal computation at boundary conditions on the model results. The differences in value of the original $H(M_2)$ that was determined in Table 4.1 of $\pm 10\%$ and $\pm 50\%$ are considered. The computational results are shown in Table 6.3 and Table 6.4, Table II.15 to Table II.18 and Figure II.7 to Figure II.9 in Appendix II.

From Table 6.3, if the error in the value $H(M_2)$ is 10%, the errors of the computed velocity and tidal prism will be about 3%. If the error in the value $H(M_2)$ is 50%, the errors of the computed velocity and tidal prism will be about 15%. So, the relative errors of the computed velocity and tidal prism are about 1/3 of the relative error made to $H(M_2)$. These errors are minor because they can be eliminated with a proper observed data set of tidal water level through which higher accuracy of tidal parameters can be obtained.

It also can be seen that, the increment of the amplitude $H(M_2)$ increases the tidal range. Therefore, the tidal prisms and flow velocities in the inlets will increase as consequent.

Table 6.2. List of the simulations with sea water level at the downstream boundaries

Simulation ID	Description
SZ01	Astronomical Tides
SZ03	Tides with only 50% of $H(M_2)$
SZ04	Tides with only 90% of $H(M_2)$
SZ05	Tides with 110% of $H(M_2)$
SZ06	Tides with 150% of $H(M_2)$

Table 6.3. Effect of the M_2 tidal parameter on the tidal prism in the dry season

Scenario	Tidal prism	Thuan An	Hoa Duan	Tu Hien	Total
Cross-sectional Area	$A(m^2)$	4200	1868	826	
SZ01: Astro. tides	$P(10^6 m^3)$	32.23	16.25	12.00	57.36
SZ03: Tides with only 50% of $H(M_2)$	$P(10^6 m^3)$	27.12	13.91	9.74	47.75
	$\Delta P/P$ (%)	-15.8	-14.4	-18.9	-16.8
SZ04: Tides with only 90% of $H(M_2)$	$P(10^6 m^3)$	31.19	15.77	11.58	55.43
	$\Delta P/P$ (%)	-3.2	-2.9	-3.5	-3.4
SZ05: Tides with 110% of $H(M_2)$	$P(10^6 m^3)$	33.19	16.70	12.39	59.17
	$\Delta P/P$ (%)	3.0	2.8	3.2	3.2
SZ06: Tides with 150% of $H(M_2)$	$P(10^6 m^3)$	37.10	18.44	13.91	66.29
	$\Delta P/P$ (%)	15.1	13.5	15.9	15.6

Table 6.4. Effect of the M2 tidal parameter on the maximum flow velocities at the inlets

Scenario	Inlet	Thuan An		Hoa Duan		Tu Hien	
	Phase	Flood	Ebb	Flood	Ebb	Flood	Ebb
SZ01: Astro. tides	$V_{\max}$ (m/s)	-0.59	0.60	-0.60	0.60	-0.84	1.09
SZ03: Tides with only 50% of $H(M_2)$	$V_{\max}$ (m/s)	-0.51	0.52	-0.55	0.51	-0.71	0.93
	$\%V_{\max}$ (%)	13.5	14.4	7.7	14.6	15.1	15.0
SZ04: Tides with only 90% of $H(M_2)$	$V_{\max}$ (m/s)	-0.57	0.59	-0.59	0.59	-0.81	1.06
	$\%V_{\max}$ (%)	3.1	2.9	1.9	2.8	3.6	2.7
SZ05: Tides with 110% of $H(M_2)$	$V_{\max}$ (m/s)	-0.61	0.62	-0.61	0.62	-0.87	1.12
	$\%V_{\max}$ (%)	2.8	2.6	2.3	2.8	3.8	2.8
SZ06: Tides with 150% of $H(M_2)$	$V_{\max}$ (m/s)	-0.67	0.68	-0.66	0.68	-0.99	1.23
	$\%V_{\max}$ (%)	13.7	13.1	11.4	12.2	17.8	13.2

6.1.3. Effects of the sea level rise

According to the UNDP VIE/97/002 Project report “Strategy and Action Plan for Disaster Mitigation in Vietnam” (VIWRR, 2000), sea level rise in the area of Vietnamese coast is about 2.5 – 3.0 mm/year. Sea level rise may effect on the hydraulic conditions of the lagoon and inlets. To investigate effects of sea level rises to the hydraulic conditions of the lagoon and inlets, some computational scenarios are considered as in Table 6.5. Also, computations are taking into account the closure of the Hoa Duan inlet:

HD0 – The Hoa Duan inlet is closed;

HD1 – The Hoa Duan inlet is opened.

Table 6.5. Computational scenarios of sea level rises

Simulation ID	Description
SZ01	Astronomical Tides
SZ12	Astronomical Tides + Additional sea level rise 0.1m
SZ13	Astronomical Tides + Additional sea level rise 0.2m
SZ14	Astronomical Tides + Additional sea level rise 0.5m

6.1.3.1. Case of the Hoa Duan inlet is closed (HD0)

Computational results for difference scenarios of sea level rises in case of the Hoa Duan inlet is closed are shown in Table 6.6 and Table 6.7, Table II.19 to Table II.22 and Figure II.10 to Figure II.11 in Appendix II. From these results, effects of sea level rises on the tidal prism and flow velocity at the inlets as follows:

- The tidal prism of the inlets will increase about 4% for every 0.1m of sea level rise.
- For every 0.1m of sea level rise, the maximum flood and ebb velocities at the Thuan An and Tu Hien inlets will increase about 2.5% and 1.0%, respectively.

Table 6.6. Effect of the sea level rise on the tidal prism the dry season from January to August

Scenario	Tidal prism	Thuan An	Hoa Duan	Tu Hien	Total
Cross-sectional Area	$A(m^2)$	4200	closed	826	
SZ01-HD0: Astro. tides	$P(10^6 m^3)$	45.91		12.21	55.15
SZ12-HD0: Additional sea level rise of 0.1m	$P(10^6 m^3)$	47.82		12.64	57.55
	$\Delta P/P$ (%)	4.2		3.5	4.4
SZ13-HD0: Additional sea level rise of 0.2m	$P(10^6 m^3)$	49.62		13.07	59.86
	$\Delta P/P$ (%)	8.1		7.1	8.6
SZ14-HD0: Additional sea level rise of 0.5m	$P(10^6 m^3)$	54.45		14.37	66.46
	$\Delta P/P$ (%)	18.6		17.7	20.5

Table 6.7. Effect of the sea level rise on the maximum flow velocities at the inlets

Scenario	Inlet	Thuan An		Hoa Duan		Tu Hien	
	Phase	Flood	Ebb	Flood	Ebb	Flood	Ebb
SZ01-HD0: Astro. tides	V_{max} (m/s)	-0.82	0.84			-0.85	1.10
SZ12-HD0: Additional sea level rise of 0.1m	V_{max} (m/s)	-0.84	0.86			-0.86	1.11
	$\%V_{max}$ (%)	2.9	2.4			0.9	1.2
SZ13-HD0: Additional sea level rise of 0.2m	V_{max} (m/s)	-0.87	0.88			-0.86	1.12
	$\%V_{max}$ (%)	5.6	4.5			1.8	2.2
SZ14-HD0: Additional sea level rise of 0.5m	V_{max} (m/s)	-0.92	0.92			-0.89	1.15
	$\%V_{max}$ (%)	12.3	9.6			4.4	4.9

6.1.3.2. Case of the Hoa Duan inlet is opened (HD1)

Computation results for difference scenarios of sea level rises in the case of the Hoa Duan inlet is opened are shown in Table 6.8 and Table 6.9, Table II.23 to Table II.26 and Figure II.12 to Figure II.14 in Appendix II. From these results, effects of sea level rises on the tidal prism and flow velocity at the inlets as follows:

- The tidal prism of the inlets will increase about 4.5% at Thuan An and Hoa Duan and about 3.3% at Tu Hien for every 0.1m of sea level rise.
- For every 0.1m of sea level rise, the maximum flood and ebb velocities at the Thuan An and Hoa Duan inlets will increase about 2% to 3%, the maximum flood and ebb velocities at the Tu Hien will increase about 1%.

From these results, it can be seen that in the next 100 years, if sea level rise is about 0.3 m, the tidal prisms in the inlets may increase 10 - 15%. This does not take into account the sedimentation process of the lagoons. The deposition inside the lagoon reduces the lagoon volume so it also reduces the tidal prism. From the model results with the situation of the inlet cross sections in 2000, the maximum flow velocity at the Thuan An inlet may increase about 6 - 10%, the maximum flow velocity at the Tu Hien inlet may increase about 6 - 10%. In

fact, the increment of the maximum flow velocities in the inlets depend on the sea level rise is not relevant because the inlet cross sections would also change in an adaptable way. The inlet geometry is a most variable factor that depends very much on the actions of waves, littoral drift and river floods rather than sea level rise.

Table 6.8. Effect of the sea level rise on the tidal prism the dry season

Scenario		Thuan An	Hoa Duan	Tu Hien	Total
Cross-sectional Area	$A(m^2)$	4200	1868	826	
SZ01-HD1: Astro. tides	$P(10^6 m^3)$	32.23	16.25	12.00	57.36
SZ12-HD1: Additional sea level rise of 0.1m	$P(10^6 m^3)$	33.61	17.01	12.40	59.98
	$\Delta P/P$ (%)	4.3	4.7	3.3	4.6
SZ13-HD1: Additional sea level rise of 0.2m	$P(10^6 m^3)$	34.91	17.75	12.80	62.50
	$\Delta P/P$ (%)	8.3	9.2	6.7	9.0
SZ14-HD1: Additional sea level rise of 0.5m	$P(10^6 m^3)$	38.26	19.82	14.01	68.42
	$\Delta P/P$ (%)	18.7	22.0	16.8	19.3

Table 6.9. Effect of the sea level rise on the maximum flow velocities at the inlets

Scenario	Inlet	Thuan An		Hoa Duan		Tu Hien	
	Phase	Flood	Ebb	Flood	Ebb	Flood	Ebb
SZ01-HD1: Astro. tides	V_{max} (m/s)	-0.59	0.60	-0.60	0.60	-0.84	1.09
SZ12-HD1: Additional sea level rise of 0.1m	V_{max} (m/s)	-0.61	0.62	-0.61	0.61	-0.84	1.10
	$\%V_{max}$ (%)	3.0	2.3	2.9	1.7	0.9	0.9
SZ13-HD1: Additional sea level rise of 0.2m	V_{max} (m/s)	-0.62	0.63	-0.63	0.62	-0.85	1.11
	$\%V_{max}$ (%)	5.7	4.3	5.4	3.1	1.9	1.8
SZ14-HD1: Additional sea level rise of 0.5m	V_{max} (m/s)	-0.66	0.66	-0.66	0.64	-0.88	1.14
	$\%V_{max}$ (%)	12.2	8.9	11.1	5.9	4.9	4.9

6.1.4. Effects of inlet openings

Table 6.10. Computational scenarios of inlet openings

Inlet opening scenario	Thuan An			Hoa Duan			Tu Hien		
	$A(m^2)$	B(m)	d(m)	$A(m^2)$	B(m)	d(m)	$A(m^2)$	B(m)	d(m)
SO01	4200	535	12	1868	420	8	826	189	6.5
SO02	4200	535	12	<i>closed</i>	<i>closed</i>	<i>closed</i>	826	189	6.5
SO03	<i>closed</i>	<i>closed</i>	<i>closed</i>	1868	420	8	826	189	6.5
SO04	1468	344	6	597	217	4	826	189	6.5
SO05	1468	344	6	<i>closed</i>	<i>closed</i>	<i>closed</i>	826	189	6.5
SO06	<i>closed</i>	<i>closed</i>	<i>closed</i>	597	217	4	826	189	6.5

Table 6.11. Effect of inlet openings on the tidal prism the dry season

Inlet opening scenario	Tidal prism	Thuan An	Hoa Duan	Tu Hien	Total
SO01:Thuan An:B=535m,A=4200m ² ; Hoa Duan:B=420m,A=1868m ²	P(10 ⁶ m ³)	32.22	16.26	12.00	57.36
SO02:Thuan An:B=535m,A=4200m ² ; Hoa Duan: closed	P(10 ⁶ m ³)	45.91		12.21	55.15
	$\Delta P/P$ (%)	42.5		1.7	-3.8
SO03:Thuan An: closed; Hoa Duan:B=420m,A=1868m ²	P(10 ⁶ m ³)		33.76	12.05	42.83
	$\Delta P/P$ (%)		107.6	0.5	-25.3
SO04:Thuan An:B=344m; Hoa Duan:B=217m	P(10 ⁶ m ³)	25.72	11.14	12.10	45.44
	$\Delta P/P$ (%)	-20.2	-31.5	0.8	-20.8
SO05:Thuan An:B=344m; Hoa Duan: closed	P(10 ⁶ m ³)	30.25		12.14	38.75
	$\Delta P/P$ (%)	-6.1		1.2	-32.4
SO06:Thuan An: closed; Hoa Duan:B=217m	P(10 ⁶ m ³)		15.70	12.26	22.64
	$\Delta P/P$ (%)		-3.5	2.2	-60.5

Table 6.12. Effect of inlet openings on the maximum flow velocities at the inlets

Inlet opening scenario	Inlet	Thuan An		Hoa Duan		Tu Hien	
	Phase	Flood	Ebb	Flood	Ebb	Flood	Ebb
SO01:Thuan An:B=535m; Hoa Duan:B=420m	V _{max} (m/s)	-0.59	0.60	-0.60	0.60	-0.84	1.09
SO02:Thuan An:B=535m; Hoa Duan: closed	V _{max} (m/s)	-0.82	0.84			-0.85	1.10
	%V _{max} (%)	39.0	39.0			1.6	0.7
SO03:Thuan An: closed; Hoa Duan:B=420m	V _{max} (m/s)			-1.20	1.26	-0.84	1.08
	%V _{max} (%)			100.5	109.7	0.0	0.6
SO04:Thuan An:B=344m; Hoa Duan:B=217m	V _{max} (m/s)	-1.20	1.32	-1.16	1.23	-0.84	1.09
	%V _{max} (%)	104.3	118.8	94.1	103.7	0.5	0.2
SO05:Thuan An:B=344m; Hoa Duan: closed	V _{max} (m/s)	-1.39	1.51			-0.84	1.08
	%V _{max} (%)	136.3	150.3			0.4	0.9
SO06:Thuan An: closed; Hoa Duan:B=217m	V _{max} (m/s)			-1.59	1.60	-0.79	1.04
	%V _{max} (%)			165.5	165.7	5.9	4.4

To see the influences of inlet openings on the hydraulic conditions of the lagoon and inlets, the following computation scenarios of the inlet openings as shown in Table 6.10. The results of these scenarios are shown in Table 6.11, Table 6.12, from Table II.27 to Table II.30 and Figure II.15 to Figure II.17 in Appendix II (Hydraulic Simulation Results). From these results, the following conclusions can be made:

- Effects of the Thuan An and Hoa Duan inlets on the Tu Hien inlet are very small. With the different openings of the Thuan An and Hoa Duan inlets, the tidal prism and the flow velocity in the Tu Hien inlet change only a little (less than 6%). So the Tu Hien inlet can be considered independent with the Thuan An and Hoa Duan inlets.

- If only the Hoa Duan inlet is closed, the tidal prism and the maximum flow velocity at the Thuan An inlet will increase from 15% to 40% (depends on its cross sectional area) in comparison with the case of both inlets are opened.
- If only the Thuan An inlet is closed, the tidal prism and the maximum flow velocity at the Hoa Duan inlet will increase from 30% to 100% (depends on its cross sectional area) in comparison with the case of both inlets are opened.
- If the cross sectional areas of both Thuan An and Hoa Duan inlets reduce 30 to 35%, the maximum flow velocities at these inlets will increase about 100% but the tidal prisms will reduce from 20% to 30%.
- The scenario SO01 corresponding to the situation of the inlets after the November 1999 flood event has results of the maximum flow velocities at both Thuan An and Hoa Duan inlets are about 0.6 m/s that are quite small for sediment flushing. If the cross sections of both inlets reduce, or one of these inlet is closed, the maximum velocities at these inlets will increase up to 0.8 – 1.3 m/s as in scenarios SO02 to SO04. This order of the flow velocity is required for sediment flushing to maintain the inlets.

6.2. THE HYDRAULIC CHARACTERISTICS OF THE SYSTEM IN AN EXTREME CONDITION OF FLOOD

The flood of November 1999 is used for consideration of hydraulic characteristics of the system in an extreme condition. Different scenarios of storm surges and inlet openings are taken into account in computation.

6.2.1. The flood of November 1999 with different scenarios of storm surges

The scenarios of sea water level and storm surges are listed in Table 6.13. The computation results are arranged in Table 6.14 to Table II.9 to Table II.11 and Figure II.15 to Figure II.17 in Appendix II.

From the model results, it can be seen that the storm surges increase fluctuation of the flow discharge through the inlets, the maximum discharges during the ebb and flood tides are increased in magnitude.

Due to increment of sea water level, the difference in water level between the sea and the lagoon is decreased and the cross sectional areas of the inlets are increased, therefore, the maximum flow velocity in the inlets decrease accordingly.

During the 1999 flood event, the Tu Hien inlet was widened. But the obstruction of the ebb tidal delta at the end of the Thuy Tu lagoon that relatively separates the Cau Hai lagoon from others. These are the reasons for the water from the sea still enters the Cau Hai lagoon during the flood.

Table 6.13. List of the simulations with sea water level at the downstream boundaries

Simulation ID	Description
SZ01	Astronomical Tides
SZ02	Astronomical Tides with mean water level is 0m
SZ15	Astronomical Tides + Additional storm surge of 1.0m
SZ16	Astronomical Tides + Additional storm surge of 1.5m
SZ17	Astronomical Tides + Additional storm surge of 2.0m

Table 6.14. Effect of the storm surges on the maximum flow velocities at the inlets

Scenario	Inlet	Thuan An		Hoa Duan		Tu Hien	
	Phase	Flood	Ebb	Flood	Ebb	Flood	Ebb
SZ01: Astronomical tides	$V_{\max}$ (m/s)	0.30	2.37	0.10	1.77	-1.34	1.49
SZ02: Tides with mean WL=0	$V_{\max}$ (m/s)	0.34	2.41	0.02	1.78	-0.79	1.91
	% $V_{\max}$ (%)	12.8	1.9	79.3	0.3	41.0	28.5
SZ15: Additional storm surge of 1.0m	$V_{\max}$ (m/s)	0.30	2.27	0.15	1.72	-1.44	1.21
	% $V_{\max}$ (%)	2.7	4.3	47.7	3.1	7.6	18.7
SZ16: Additional storm surge of 1.5m	$V_{\max}$ (m/s)	0.29	2.22	0.15	1.69	-1.49	1.03
	% $V_{\max}$ (%)	5.9	6.2	48.7	4.5	11.5	30.7
SZ17: Additional storm surge of 2.0m	$V_{\max}$ (m/s)	0.26	2.19	0.16	1.68	-1.53	0.80
	% $V_{\max}$ (%)	15.1	7.3	54.4	5.4	14.6	46.3

6.2.2. The flood of November 1999 with different scenarios of inlet openings

The difference scenarios of the Thuan An and Hoa Duan inlets are simulated during the 1999 flood event as in Table 6.15. These include

- Scenario SO08: situation of the inlets before the flood of November 1999
- Scenario SO07: scenario SO08 with the opening of the Hoa Duan inlet
- Scenario SO01: situation of the inlets after the flood of November 1999
- Scenario SO12 to SO14: alternatives of a 1000 m wide weir at Hoa Duan with different sill elevations (-1m, 0m, 1m).
- Scenario SO12 to SO14: alternatives of a 600 m wide weir at Hoa Duan with different sill elevations (-1m, 0m, 1m).

DUFLOW cannot simulate the progress of making a new opening at Hoa Duan so the scenarios SO08, SO07 and SO01 are made to simulate three situations of the inlets separately.

A barrage (a weir or a barrier) may be constructed at Hoa Duan location that will be opened only for flood discharging from the lagoon to the sea, otherwise it will have to be closed. Scenarios SO12 to SO17 are to simulate different alternatives of this barrage with its width of

1000m and 600m and its bottom elevation is from -1m to 1m. Higher elevation of its sill cannot be simulated in DUFLOW because of a dry bed error occurs.

The results of the model for above scenarios are summarised in Table 6.16, from Table II.12 to Table II.14 and Figure II.4 to Figure II.6 in Appendix II.

From the model results, the averaged distributions of flow discharges in the Thuan An, Hoa Duan and Tu Hien inlets during the flood November 1999 are 60%, 25% and 15%, respectively.

From Table II.11 and Table II.13 in Appendix II, the maximum discharge in the Thuan An inlet when the Hoa Duan inlet is closed can reach 13000 m³/s and the velocity can reach 3.7 m/s. This due to the obstacle of the sand barrier for flood evacuation. The difference in water level between the lagoon and the sea is about 1 m (Table 5.4 in Chapter 5).

When the Hoa Duan inlet is opened, the maximum discharge in the Thuan An inlet reduces to 9500 m³/s and the velocity reduces to 2.75 m/s. The maximum discharge in the Hoa Duan inlet is about 4100 m³/s and the velocity is 1.93 m/s.

If the cross sectional area of the Thuan An inlet increases, the peak flood discharge will increase, but the maximum velocity will decrease. The flow discharge and velocity in the Hoa Duan inlet will also decrease. But the difference in water level between the lagoon and the sea is still in the order of 1 m. So the openings of the inlets are quite small to discharge a big water volume of the flood.

As can be seen from Table II.12 to Table II.14, the Thuan An and Hoa Duan inlets have a small effect on the Tu Hien inlet.

Table 6.15. List of the scenarios for inlet openings

Scenario ID	Thuan An inlet			Hoa Duan inlet			Tu Hien inlet		
	B(m)	d(m)	A(m ²)	B(m)	d(m)	A(m ²)	B(m)	d(m)	A(m ²)
SO01	535	12	4200	420	8	1868	189	6.5	826
SO07	405	11.5		420	8	1868	189	6.5	826
SO08	405	11.5		<i>closed</i>	<i>closed</i>	<i>closed</i>	189	6.5	826
SO12	535	12	4200	1000	-1	<i>weir</i>	697	1	510
SO13	535	12	4200	1000	0	<i>weir</i>	697	1	510
SO14	344	6	1468	1000	+1	<i>weir</i>	697	1	510
SO15	535	12	4200	600	-1	<i>weir</i>	697	1	510
SO16	535	12	4200	600	0	<i>weir</i>	697	1	510
SO17	344	6	1468	600	+1	<i>weir</i>	697	1	510

Table 6.16. Effect of inlet openings on the maximum flow velocities at the inlets

Scenario	Inlet	Thuan An		Hoa Duan		Tu Hien	
	Phase	Flood	Ebb	Flood	Ebb	Flood	Ebb
SO01: Thuan An: B=535m; Hoa Duan: B=420m	$V_{\max}$ (m/s)	0.30	2.37	0.10	1.77	-1.34	1.49
SO07: Thuan An: B=405m; Hoa Duan: B=420m	$V_{\max}$ (m/s)	0.36	2.75	0.13	1.93	-1.33	1.49
	$\%V_{\max}$ (%)	19.4	16.1	28.8	8.6	0.4	0.0
SO08: Thuan An: B=405m; Hoa Duan: closed	$V_{\max}$ (m/s)	0.54	3.68			-1.28	1.53
	$\%V_{\max}$ (%)	78.6	55.7			4.0	2.8
SO12: Thuan An: B=535m; Hoa Duan: Z=-1m,B=1000m	$V_{\max}$ (m/s)	0.33	2.42	0.08	1.18	-1.49	1.04
	$\%V_{\max}$ (%)	7.1	2.3	18.0	33.7	11.1	29.9
SO13: Thuan An: B=535m; Hoa Duan: Z=+0m,B=1000m	$V_{\max}$ (m/s)	0.36	2.66	0.06	1.03	-1.48	1.06
	$\%V_{\max}$ (%)	18.6	12.3	37.7	42.2	10.4	28.5
SO14: Thuan An: B=535m; Hoa Duan: Z=+1m,B=1000m	$V_{\max}$ (m/s)	0.40	2.86	0.04	0.74	-1.47	1.09
	$\%V_{\max}$ (%)	29.7	20.9	63.4	58.3	9.6	26.8
SO15: Thuan An: B=535m; Hoa Duan: Z=-1m,B=600m	$V_{\max}$ (m/s)	0.35	2.62	0.10	1.31	-1.48	1.06
	$\%V_{\max}$ (%)	14.9	10.6	4.7	26.2	10.6	28.8
SO16: Thuan An: B=535m; Hoa Duan: Z=+0m,B=600m	$V_{\max}$ (m/s)	0.38	2.78	0.07	1.10	-1.47	1.08
	$\%V_{\max}$ (%)	24.3	17.4	27.8	38.1	9.9	27.6
SO17: Thuan An: B=535m; Hoa Duan: Z=+1m,B=600m	$V_{\max}$ (m/s)	0.40	2.91	0.04	0.76	-1.47	1.09
	$\%V_{\max}$ (%)	32.5	23.0	58.1	57.0	9.5	26.3

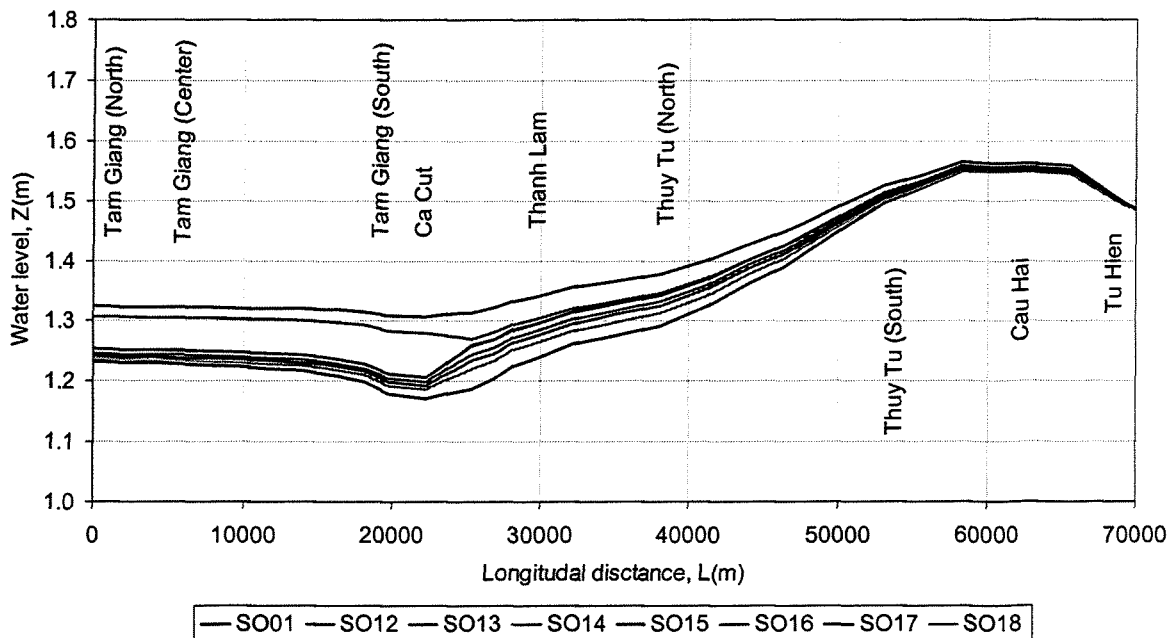


Figure 6.6. Computed water profile in the lagoons at 2/11/99 10:00

6.3. INLET STABILITY

6.3.1. Overall stability

From observed data and computed values of the tidal prisms at the inlets as mentioned in Section 6.1.1 that are arranged in Table 6.1, the inlets of the Tam Giang-Cau Hai lagoon quite fit the relationship of tidal prism versus cross-sectional area according to Jarrett (1976) as can be seen in Figure 6.7. From Figure 6.7, although the stability situations of the inlets are not good (see in Table 6.17 to Table 6.19) and the cross sections of the inlets are highly variable, the inlets are still inside the 95% confidence limits of the trend line.

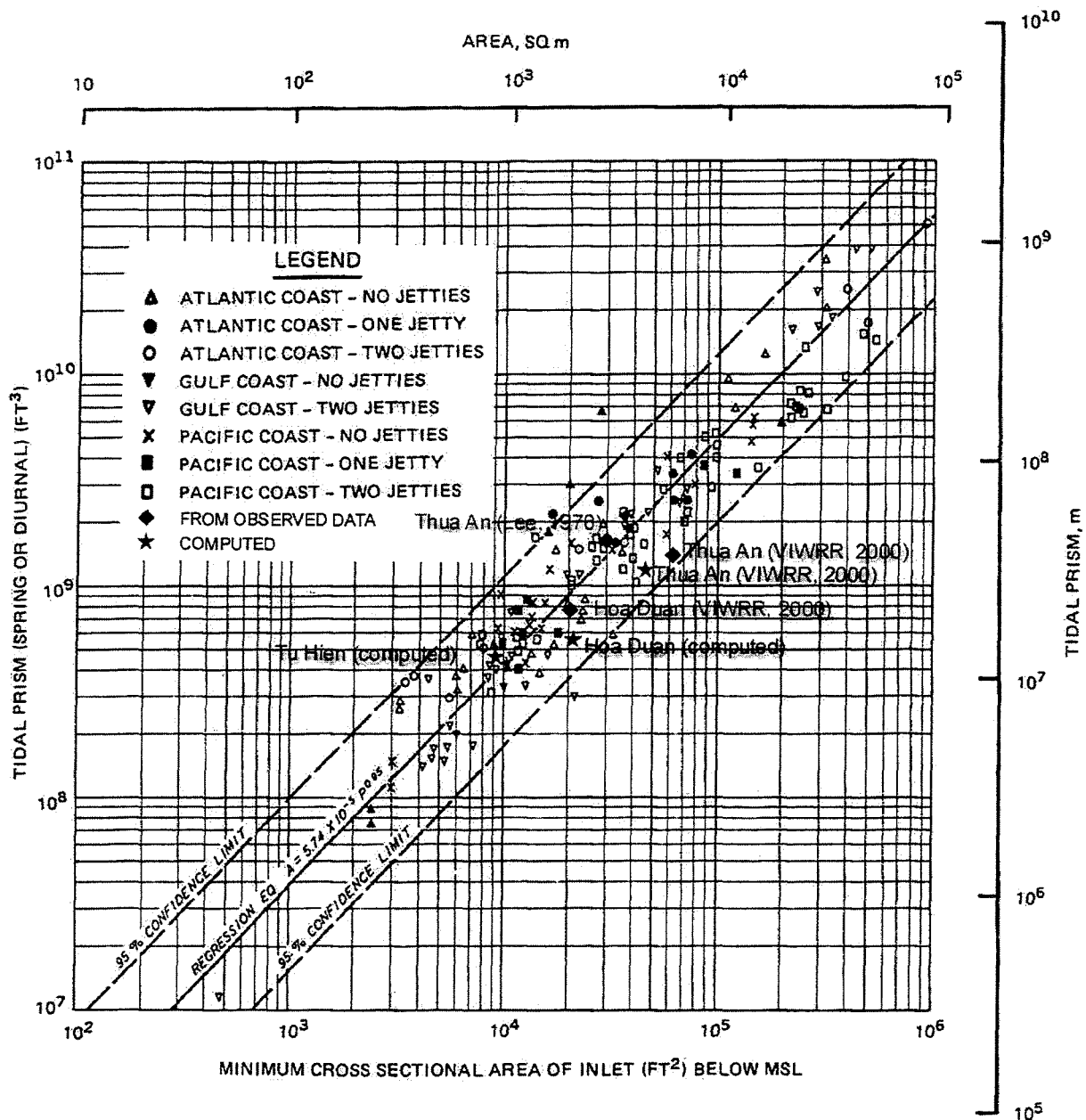


Figure 6.7. The inlets of the Tam Giang-Cau Hai lagoon on the relationship of tidal prism versus cross-sectional area for all inlets on Atlantic, gulf and Pacific coasts (after Jarrett, 1976)

The overall stabilities of the inlets according to Bruun's criteria are determined as in Table 6.17 to Table 6.19. The tidal prisms and cross sectional areas of the inlets are from observed data or computed by the model that taking into account the sea level rise for the next 100 years and effects of freshwater flows from the rivers. The amounts of littoral drift are from literature as is mentioned in Chapter 4.

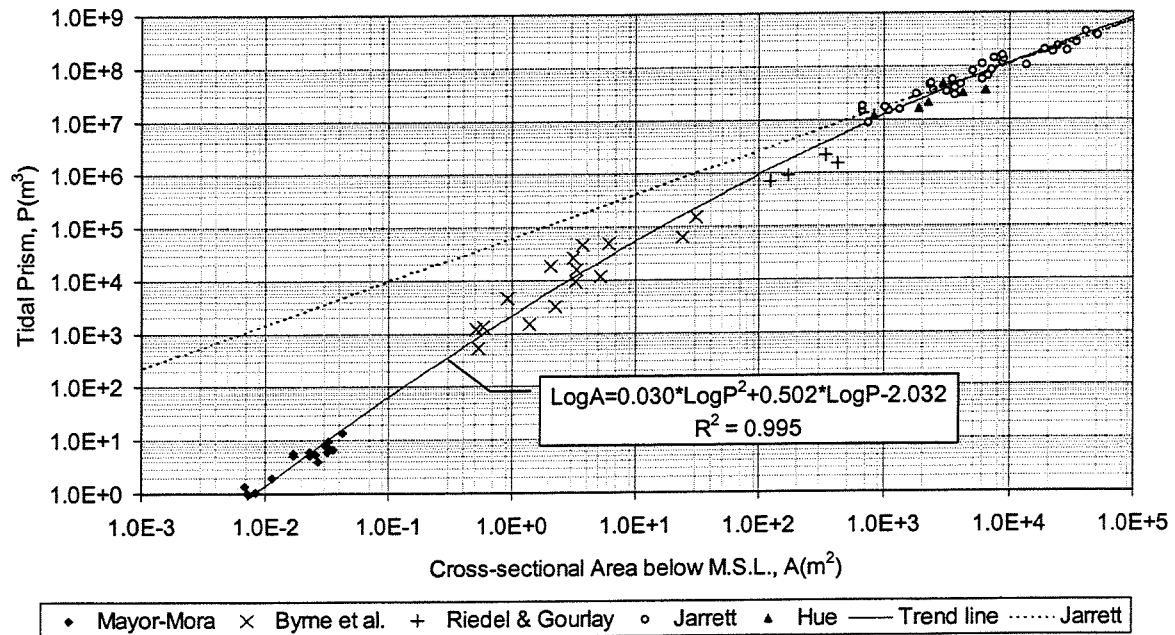


Figure 6.8. The trend line of tidal inlets (after Bruun, 1990)

Table 6.17. Overall stability situation of the Thuan An inlet with different opening scenarios

Inlet opening scenario	Tidal prism P (10^6m^3)	Maximum discharge $Q_{\max}$ (m^3/s)	Littoral drift M_{tot} ($10^6 \text{m}^3/\text{yr}$)	$\frac{P}{M_{\text{tot}}}$	Stability situation
According to Lee, 1970	47	2900	1.6	30	poor, entrance shoals
Observed in May 2000 (SO01)	36	2660	0.64 – 3.42	11 – 56	fair to poor
SO01: Thuan An: $B=535\text{m}$; Hoa Duan: $B=420\text{m}$	32 – 40	2400	0.64 – 3.42	9 – 63	fair to poor
SO02: Thuan An: $B=535\text{m}$; Hoa Duan: closed	46 – 55	3330	0.64 – 3.42	13 – 86	fair to poor
SO04: Thuan An: $B=344\text{m}$; Hoa Duan: $B=217\text{m}$	26 – 31	1800	0.64 – 3.42	8 – 48	poor
SO05: Thuan An: $B=344\text{m}$; Hoa Duan: closed	30 – 36	2080	0.64 – 3.42	9 – 56	fair to poor

From Table 6.17, the stability of the Thuan An inlet is in a “fair to poor” situation. The entrance shoals causing difficulties for navigation and flood evacuation. If the opening of the Thuan An inlet is small and the Hoa Duan inlet is opened, the stability situation of the Thuan An inlet will become “poor”. It means that the tidal prism is not enough and flow is not able to push out the sediment that enters into the inlet from sides.

Table 6.18. Overall stability situation of the Hoa Duan inlet with different opening scenarios

Inlet opening scenario	Tidal prism P (10^6m^3)	Maximum discharge $Q_{\max}$ (m^3/s)	Littoral drift M_{tot} ($10^6 \text{m}^3/\text{yr}$)	$\frac{P}{M_{\text{tot}}}$	Stability situation
Observed in May 2000 (SO01)	21	1670	0.64 – 3.42	6 – 33	poor
SO01: Thuan An:B=535m; Hoa Duan:B=420m	16 – 18	1172	0.64 – 3.42	5 – 28	poor
SO03: Thuan An: closed; Hoa Duan:B=420m	34 – 41	2352	0.64 – 3.42	10 – 64	fair to poor
SO04: Thuan An:B=344m; Hoa Duan:B=217m	11 – 13	747	0.64 – 3.42	3 – 20	poor
SO06: Thuan An: closed; Hoa Duan:B=217m	16 – 18	1009	0.64 – 3.42	5 – 28	poor

Table 6.19. Overall stability situation of the Tu Hien inlet with different opening scenarios

Inlet opening scenario	Tidal prism P (10^6m^3)	Maximum discharge $Q_{\max}$ (m^3/s)	Littoral drift M_{tot} ($10^6 \text{m}^3/\text{yr}$)	$\frac{P}{M_{\text{tot}}}$	Stability situation
SO01: Thuan An:B=535m; Hoa Duan:B=420m	12 – 14	860	0.67 – 1.21	10 – 21	poor
SO02: Thuan An:B=535m; Hoa Duan: closed	12 – 14	866	0.67 – 1.21	10 – 21	poor
SO03: Thuan An: closed; Hoa Duan:B=420m	12 – 14	855	0.67 – 1.21	10 – 21	poor
SO04: Thuan An:B=344m; Hoa Duan:B=217m	12 – 14	858	0.67 – 1.21	10 – 21	poor
SO05: Thuan An:B=344m; Hoa Duan: closed	12 – 14	850	0.67 – 1.21	10 – 21	poor
SO06: Thuan An: closed; Hoa Duan:B=217m	12 – 14	818	0.67 – 1.21	10 – 21	poor

From Table 6.18, if the Hoa Duan inlet and the Thuan An inlet are opened together, the Hoa Duan inlet will have a “poor” stability situation. The flow velocity in this inlet will be smaller than 1 m/s and the inlet will be deposited and will decline.

If only the Hoa Duan inlet is opened with a opening of 400 – 500 m (the Thuan An inlet is closed, the Tu Hien inlet is opened), the stability situation of this inlet will be “fair to poor”. It means that the inlet will be more stable but there will be still difficulties for navigation and flood evacuation causing by entrance shoals and bars. This is proved by the fact that the Hoa Duan inlet had been lasting for hundred years in periods of 1404 – 1504 and 1700 – 1897 (Tran Duc Thanh *et al.*, 2000) before the Thuan An inlet opened as can be seen in Figure 2.6 in Chapter 2.

From Table 6.19, the stability situation of the Tu Hien inlet is always “poor” and does not depend on the openings of the Thuan An inlet and the Hoa Duan inlet.

6.3.2. Gorge cross sectional stability

Beside of overall stability criteria, other stability criteria for the cross section of the inlets, e.g. $V_{mean\ max}$, is considered.

From the model result in Table 6.4, after the 1999 flood event when the Hoa Duan inlet was opened and the Thuan An inlet was widened, the flow velocity of the Thuan An inlet is $V_{mean\ max} = 0.59$ m/s is quite small for sediment flushing. If the Hoa Duan inlet is closed or both inlets are narrowed, the values of $V_{mean\ max}$ of these inlets will increase up to 1.2 – 1.6 m/s.

From these results, to maintain the value of $V_{mean\ max}$ of the Thuan An inlet in the order of 1 m/s, the cross section of the Thuan An inlet must have a width in the order of 500 m and a depth of 10 – 11 m, and the Hoa Duan inlet must be closed.

The flow velocity $V_{mean\ max}$ of the Tu Hien inlet is quite close to the value of 1 – 1.1 m/s, that is appropriate for sediment flushing.

6.3.3. Stabilisation of the inlets

From above results, the inlets are in the situation of “fair to poor” stability. Inlet entrances are shoal causing difficulties for navigation. Therefore, it is necessary to stabilise the inlets with jetties. A cross section of 500 m wide and 10 – 11 m deep is appropriate for the Thuan An inlet. The dimension of a suitable cross section for the Tu Hien inlet is 190 m wide and 6 m deep, as investigated with the model. For the stability of the Thuan An inlet, the Hoa Duan inlet must be closed.

For enhancement of flood evacuation capacity of the system, barrages with gate control may be necessarily built at the downdrift side of the inlets in associate with construction of reservoirs for flood regulation upstream of the rivers. The salt intrusion preventing structure at downstream of the Huong River is also required the consideration for flood evacuation.

Initial dredging of the inlets, ebb tidal channels in the lagoons and river mouths after construction of coastal structures is also required for navigation and flood evacuation.

Further more, the choice of inlet location and stabilisation measures must be carefully based on the study and consideration of navigation, flood evacuation, salt intrusion and morphology of the inlets and shorelines under associated effects of waves, tides, river flows, and sediment transport.

6.4. CONCLUSIONS ON THE HYDRODYNAMIC CHARACTERISTICS OF THE SYSTEM AND STABILITY OF THE INLETS

6.4.1. The hydrodynamic characteristics of the system

1. The main forces acting on hydrodynamics of the system in the dry season are tides. Effects of river flows in the dry season to hydrodynamics of the system are small. The averaged values of river flows in the dry season can be used for model boundary conditions without significant effects on the model results.
2. In the Tam Giang lagoon in dry season, the flow velocity in the northern part is quite small, from 2 – 3 cm/s and does not changed with different scenarios of sea water level nor inlet openings. The maximum flow velocity increases to about 20 cm/s at the middle part of the lagoon and increases to about 65 – 75 cm/s at the southern end of the lagoon near the Thuan An inlet. The difference in water level at two ends of the lagoon is less than 25 cm along its length of 27 km.
3. The relative errors of computed velocity and tidal prisms at the inlets are about 1/3 of the relative error made to the value of $H(M_2)$ of M_2 tidal component. That is, if the error of the M_2 magnitude is 10% then the error in computation of flow velocity and tidal prism will be about 3%. This error is small and can be eliminated because the tidal parameters can be determined precisely based on appropriate observed data of the tidal water level.
4. Sea level rises effect mainly on the inlets and water level inside lagoons. The flow velocities in the lagoons change very little under effect of sea level rise. The tidal prisms of the inlets will increase about 4% for every 0.1m of sea level rise. For the next 100 years, sea level rise may be about 0.3 m, tidal prisms of the inlets will increase by 10 – 15%. For every 0.1m of sea level rise, the maximum flood and ebb velocities at the Thuan An and Hoa Duan inlets will increase about 2.5%, the maximum flood and ebb velocities at the Tu Hien inlet will increase about 1%. In fact, the increments of the flow velocities in the inlets will not occur because the cross sections of the inlets will also change to adopt with the changes of tidal prisms.
5. The openings of the inlets are too small for flood evacuation in extreme situations. The alternatives of building a weir or a barrage at Hoa Duan cannot completely solve this problem. Other alternatives of reservoirs built upstream rivers for flood regulation must be combined. Note that topographic data for the simulations of floods have a limited reliability and accuracy as mentioned in Chapter 4. The reliability solution for the flood evacuation problem requires more accuracy of topographic and hydrologic data.

6.4.2. The stability situation of the inlets

1. The stability Thuan An inlet is in a “fair to poor” situation, according to Brunn’s criterion P/M_{tot} , with entrance shoals and bars that causing difficulties for navigation. The Tu Hien inlet is always in a “poor” stability condition. Stabilisation of the inlets with jetties is necessary.
2. For the stability of the Thuan An inlet, the Hoa Duan inlet must be closed.
3. The Tu Hien inlet is quite independent with the Thuan An and Hoa Duan inlets. So its opening is important in terms of navigation, lagoon ecology, fishery, aquaculture and flood evacuation.
4. Due to the micro-tidal regime of the area that waves and wave induced littoral drift are dominant, the additional sediment flushing by freshwater flows becomes important for maintaining the inlets.

6.5. RECOMMENDATIONS ON THE RELEVANT PROCESSES AND RELATED DATA FOR FURTHER STUDIES

6.5.1. Recommendations for the study on the system

The proper solution for the issued problems of the Tam Giang-Cau Hai lagoon system must take into account all important hydrographic and hydrodynamic aspects of such as river flows, tides, storm surges, waves, sediment transport, salt intrusion and morphology of the system. The appropriate inlet openings, location and design of stabilisation measures must be carefully based on the study and consideration of navigation, flood evacuation, salt intrusion, morphology of the inlets, and morphology (erosion/accretion) of the shorelines under associated effects of waves, tides, river flows, and sediment transport.

To study the solution for the system, beside of using the model of this study for the whole system, it is recommended to employ a morphologic model (preferably 2D) for in detail simulation of the inlets and their vicinity taking into account of effects of tides, waves, river flows, flow circular by wind, density current, sediment transport which to answer the following questions:

1. What are the effects of these processes (river flows, tides, wind, waves, density current, sediment transport) on the hydrodynamics and morphology of the inlets and their vicinity?
2. What are the causes and the mechanisms of inlet migration, shoal and close? Which are the contributions of long-shore sediment transport, cross-shore sediment transport by waves, sediment transport in the lagoons and inlets by tidal currents and river flows, siltation by salt intrusion to the instability of the inlets?
3. What are the causes and the mechanisms of a breakthrough in the sand barriers? Which are the contributions of river floods, flow overtopping, seepage, geologic instability, erosion by waves, storm surges in the sea and wind set-up in the lagoons during a typhoon to the possibility of a breakthrough?
4. How do density currents and salt intrusion affect on the distribution of flow velocity, sediment transport, erosion/siltation in the inlets and in the lagoons?

5. What is the solution for inlet stabilisation for the purposes of navigation, flood control, salt intrusion? How are the configuration and locations of the inlets and coastal structures? How are the effects of inlet stabilisation measures on erosion/accretion of the shoreline?

6.5.2. Recommendations for the data collection

Research on hydrodynamics and morphology of the system requires more data to be collected and more observations to be done. Depending on the financial budget for observations, the following priority order can be used:

1. Collecting data of waves (wave height, period, and direction); currents (speed, direction, and patterns) in the vicinity of inlets, near-shore and lagoons; water level of tides in the sea, vicinity of inlets and inside lagoons; topography and bathymetry; sediment transport (bed load, suspended load; total transport) longshore, in the inlets, rivers and lagoons; water quality (salinity); river discharges; wind (speed and direction); characteristics of sediment (in the inlets, beaches, lagoons and rivers), occurrences and magnitudes of storm surges, if available. Offshore wind and wave data at Con Co Island, flow discharges and water levels in the rivers, and some more other data can be obtained from HMS.
2. Monitoring the migrations of the inlets, changes of coastline and beach profiles. Measurements of coastline, beach profiles and sand dunes are necessary for erosion/accretion and sediment budget inventory to estimate long-shore sediment transports and its effect to the inlets. Observations of the inlet location, cross-sections, channels are suggested to be done frequently, especially after each flood from upstream rivers. Bottom level, inlet main channel, bed forms are needed to be surveyed.
3. The available observed tidal data are too short for a tidal analysis. More observations of ocean tidal water level at Thuan An and Tu Hien inlets are needed to be carried out with a standard period of continuous measurement (30 or 369 days). The fixed locations of measurement should be chosen so the water level is not effected by the flow from the rivers. The observations are also carried out during typhoons for storm surge analysis purpose.
4. Observations of sediment transport from the rivers into the lagoon, sediment transport at the inlets are necessary to be done in both flood and dry seasons.
5. Because of the strong stratification in the lagoon, observations of density current, salinity at the inlets, inside the lagoon and in the rivers are also important.
6. Flow data of the rivers discharge to the lagoon, especially the O Lau River need to be observed more. Observation of water level of the O Lau River is necessary to be done in a period of one year. Flow discharge is necessary to be observed in flood season from September to December. Information on flow of other rivers can be collected more from HMS gauging stations.

Chapter 7. CONCLUSIONS AND RECOMMENDATIONS

7.1. CONCLUSIONS

1. In general, the objectives of the study were attained. These include setting up a numerical model to investigate the hydraulic behaviour of the Tam Giang-Cau Hai lagoon and tidal inlet system; evaluating the stability of the inlet within these boundary conditions; and evaluating the data available and to suggest which processes are relevant and which data are required for the next step of the study.
2. Due to the limitation of the data available for the study, the model is restricted on the hydrodynamic characteristics of the lagoons and the inlets under associated effects of the boundary conditions such as sea water level (tides, sea level rise, storm surges), river flows, and inlet openings. Effects of wind, waves, long-shore currents, density currents, salt intrusion, sediment transport, and morphological processes are not taken into account.
3. Based on the data available for this study, the numerical model of the Tam Giang-Cau Hai lagoon and tidal inlet system has been set up, calibrated and validated. Model calibration shows that topography and bottom roughness are the most sensitive factors effecting on the model results. But there is no data available in the lagoon system for model calibration and validation. Hence the variation of bottom roughness in the system, that may effect on the hydraulic characteristics, could not be taken into account in the study. Therefore, more observations of water levels in the system are necessary to refine the model. Effects of other model parameters such as time step and weighting coefficient θ on the results are not significant. The time step of $\Delta t = 10$ minutes is appropriate for the stability and accuracy of the results. The model has been validated with both extreme condition of river flood flow and normal condition of river flow in the dry season. Validation of the model indicates that the model (including DUFLOW package, schematisation, topographic data and model parameters) is acceptable and can be used for simulation hydrodynamic behaviour of the system taking into account effects of tides and river flows.
4. Model results indicate that river flows are the most important acting force of the system during floods. Tides, storm surges and inlet openings are also important factors changing the hydrodynamic characteristics of the system in these extreme conditions. In the normal condition of river flow in the dry season lasting 8 months from January to August, the most important factors influencing the hydrodynamic characteristics of the system are tides, sea level rise and inlet openings. Tidal water level, river floods, and sediment transport are the most sensitive acting forces influencing the stability of the inlets.
5. Analysis of the observed data available shows that the accuracy of the data on topography of the flood plain area, cross sections of the rivers, tidal water levels in the vicinity of the inlets are low. However, effect of this on the model results is minor. Effects of the inaccuracy of the tidal parameters on the model results are minor and can be eliminated by doing more observations of ocean tides. Effects of the inaccuracy of the river flows in the dry season on the model results are also minor because the volume of freshwater from the rivers discharging through the inlets is only about 7.5% of the total water exchanged between the lagoons and the ocean every day in average.

6. It can be predicted that in the next 100 years, if sea level rise in the area is 0.3 m, tidal prisms of the inlets will increase by 10 – 15%. But this result does not take into account the sedimentation process in the lagoons and human activities (shrimp farms, land reclamation) that reduce the storage volume of the lagoon.
7. The stability Thuan An inlet is in a “fair to poor” situation, according to Brunn’s criterion P/M_{tot} , with entrance shoals and bars that causing difficulties for navigation. The Tu Hien inlet is always in a “poor” stability condition. Stabilisation of the inlets with jetties is necessary.
8. Inlet opening investigation with the model shows that a cross section of 500 m wide and 10 – 11 m deep is appropriate for the Thuan An inlet. The dimension of a suitable cross section for the Tu Hien inlet is about 190 m wide and 6 m deep. For the stability of the Thuan An inlet, the Hoa Duan inlet must be closed.
9. The openings of the inlets are too small for evacuating of high river flood discharges. The difference in water level between the lagoon and the sea at the Thuan An inlet may be in the order of 1 m. This causes flow velocity in the Thuan An inlet as high as the order of 2.5 – 3 m/s. High hydraulic gradient and flow velocity erode the existing inlets to widen and deepen them and will create breakthroughs in the sand barriers to open new inlets if overtopping occurs.
10. The obstacles of the sand barriers, inlet openings and storm surges at the sea worsen the inundation situation in the Hue delta. To enhance the flood evacuation capacity of the system, barrages with gate control may be necessarily built at the downdrift side of the inlets in association with construction of reservoirs for flood regulation upstream of the rivers. The saltwater preventing structure at downstream of the Huong river is required also the consideration for flood evacuation.
11. The hydraulic characteristics of the Tu Hien inlet are relatively independent with the openings of the Thuan An and Hoa Duan inlets. The reason of this is the obstacle caused by the ebb-tidal delta in south Thuy Tu lagoon. Therefore its opening is important in terms of navigation, lagoon ecology, fishery, aquaculture and flood evacuation.
12. The model results show that the flow circulation in the northern part of the Tam Giang lagoon and in the Cau Hai lagoon in the normal condition are quite weak. This is an auspicious condition for sedimentation of these lagoons.

7.2. RECOMMENDATIONS

1. The model can be use for hydrodynamic simulation of the Tam Giang-Cau Hai lagoon and tidal inlet system under effects of river flows and sea water levels. For enhancement of model results, more checkpoints should be located inside the system for refining model calibration and validation. More observations of tidal water level at the sea boundaries and water level at these checkpoints are necessarily done. For better simulation of floods, the model data on topography required to be updated with the last measurement of the area.
2. The proper solution for the issued problems of the Tam Giang-Cau Hai lagoon system must take into account all important hydrographic and hydrodynamic aspects of such as river flows, tides, storm surges, waves, sediment transport, salt intrusion and morphology

of the system. The appropriate inlet openings, location and design of stabilisation measures must be carefully based on the study and consideration of navigation, flood evacuation, salt intrusion, morphology of the inlets, and morphology (erosion/accretion) of the shorelines under associated effects of waves, tides, river flows, and sediment transport.

3. To study the solution for the system, beside of using the model of this study for the whole system, it is recommended to employ a morphologic model (preferably 2D) for in detail simulation of the inlets and their vicinity taking into account of effects of tides, waves, river flows, flow circular by wind, density current, sediment transport which to answer the following questions:
 - a. What are the effects of these processes (river flows, tides, wind, waves, density current, sediment transport) on the hydrodynamics and morphology of the inlets and their vicinity?
 - b. What are the causes and the mechanisms of inlet migration, shoal and close? Which are the contributions of long-shore sediment transport, cross-shore sediment transport by waves, sediment transport in the lagoons and inlets by tidal currents and river flows, siltation by salt intrusion to the instability of the inlets?.
 - c. What are the causes and the mechanisms of a breakthrough in the sand barriers? Which are the contributions of river floods, flow overtopping, seepage, geologic instability, erosion by waves, storm surges in the sea and wind setup in the lagoons during a typhoon to the possibility of a breakthrough?.
 - d. How do density currents and salt intrusion affect on the distribution of flow velocity, sediment transport, erosion/siltation in the inlets and in the lagoons?
 - e. What is the solution for inlet stabilisation for the purposes of navigation, flood control, salt intrusion? How are the configuration and locations of the inlets and coastal structures? How are the effects of inlet stabilisation measures on erosion/accretion of the shoreline?.
4. Research on hydrodynamics and morphology of the system requires more data to be collected and more observations to be done. Depending on the financial budget for observations, the following priority order can be used:
 - f. Collecting data of waves (wave height, period, and direction); currents (speed, direction, and patterns) in the vicinity of inlets, near-shore and lagoons; water level of tides in the sea, vicinity of inlets and inside lagoons; topography and bathymetry; sediment transport (bed load, suspended load; total transport) longshore, in the inlets, rivers and lagoons; water quality (salinity); river discharges; wind (speed and direction); characteristics of sediment (in the inlets, beaches, lagoons and rivers), occurrences and magnitudes of storm surges, if available. Offshore wind and wave data at Con Co Island, flow discharges and water levels in the rivers, and some more other data can be obtained from HMS.
 - g. Monitoring the migrations of the inlets, changes of coastline and beach profiles. Measurements of coastline, beach profiles and sand dunes are necessary for erosion/accretion and sediment budget inventory to estimate long-shore sediment transports and its effect to the inlets. Observations of the inlet location, cross sections, channels are suggested to be done frequently, especially after each flood from upstream rivers. Bottom level, inlet main channel, bed forms are needed to be surveyed.

- h. The available observed tidal data are too short for a tidal analysis. More observations of ocean tidal water level at Thuan An and Tu Hien inlets are needed to be carried out with a standard period of continuous measurement (30 or 369 days). The fixed locations of measurement should be chosen so the water level is not effected by the flow from the rivers. The observations are also carried out during typhoons for storm surge analysis purpose.
- i. Observations of sediment transport from the rivers into the lagoon, sediment transport at the inlets are necessary to be done in both flood and dry seasons.
- j. Because of the strong stratification in the lagoon, observations of density current, salinity at the inlets, inside the lagoon and in the rivers are also important.
- k. Flow data of the rivers discharge to the lagoon, especially the O Lau River need to be observed more. Observation of water level of the O Lau River is necessary to be done in a period of one year. Flow discharge is necessary to be observed in flood season from September to December. Information on flow of other rivers can be collected more from HMS gauging stations.

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Appendix I. BASIC DATA

I.1. GEOMORPHOLOGICAL EVOLUTION OF THE SYSTEM

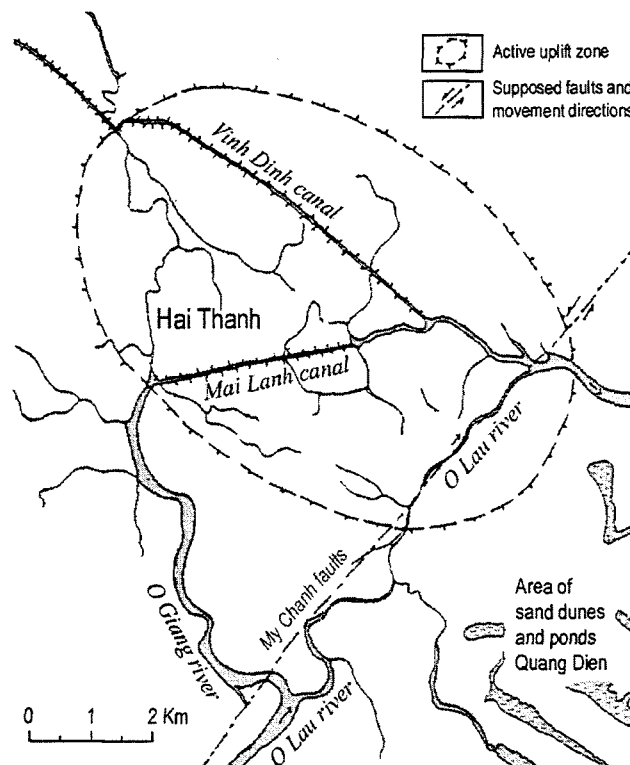


Figure I.1. Effect of the Hai Thanh uplifting zone on the O Lau and O Giang river system (Nguyen Dinh Hoe *et al.*, 1995)

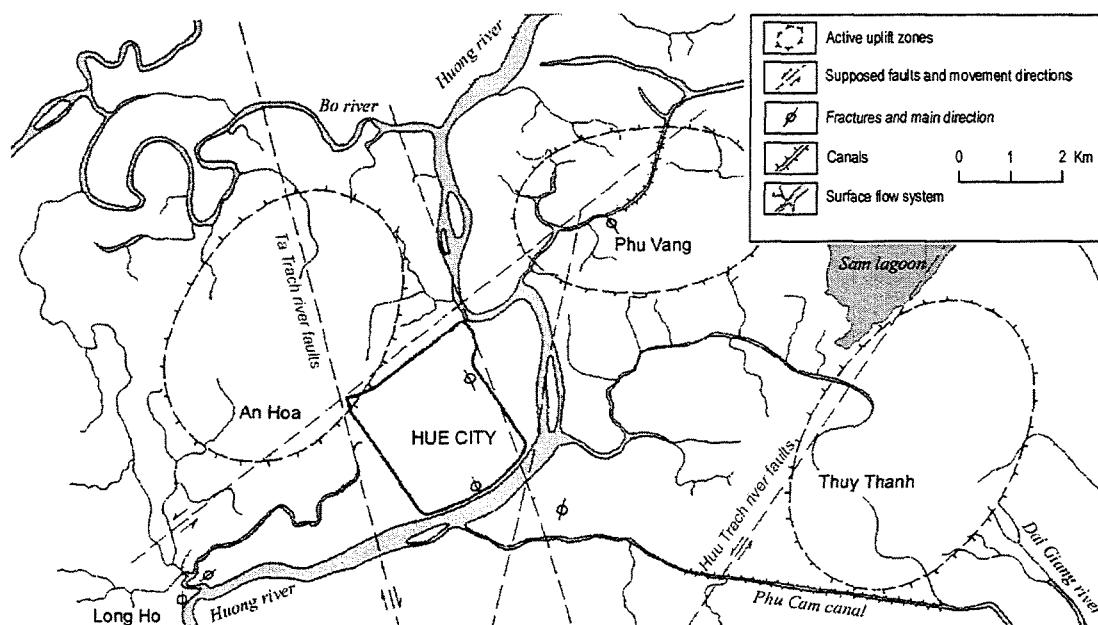


Figure I.2. Local uplifting activities in the area of Hue city (Nguyen Dinh Hoe *et al.*, 1995)

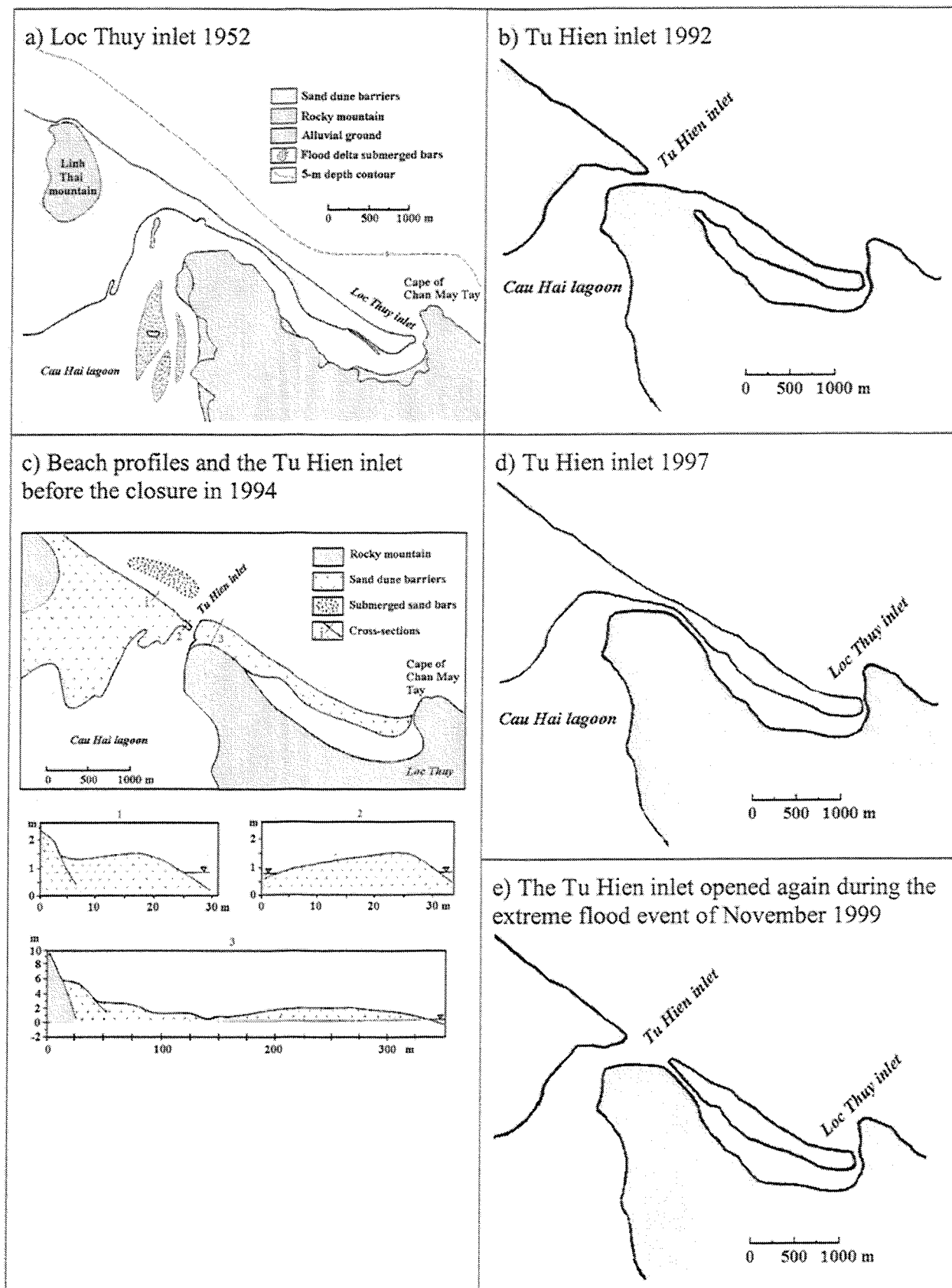


Figure I.3. Configuration of the Tu Hien inlet at different time periods

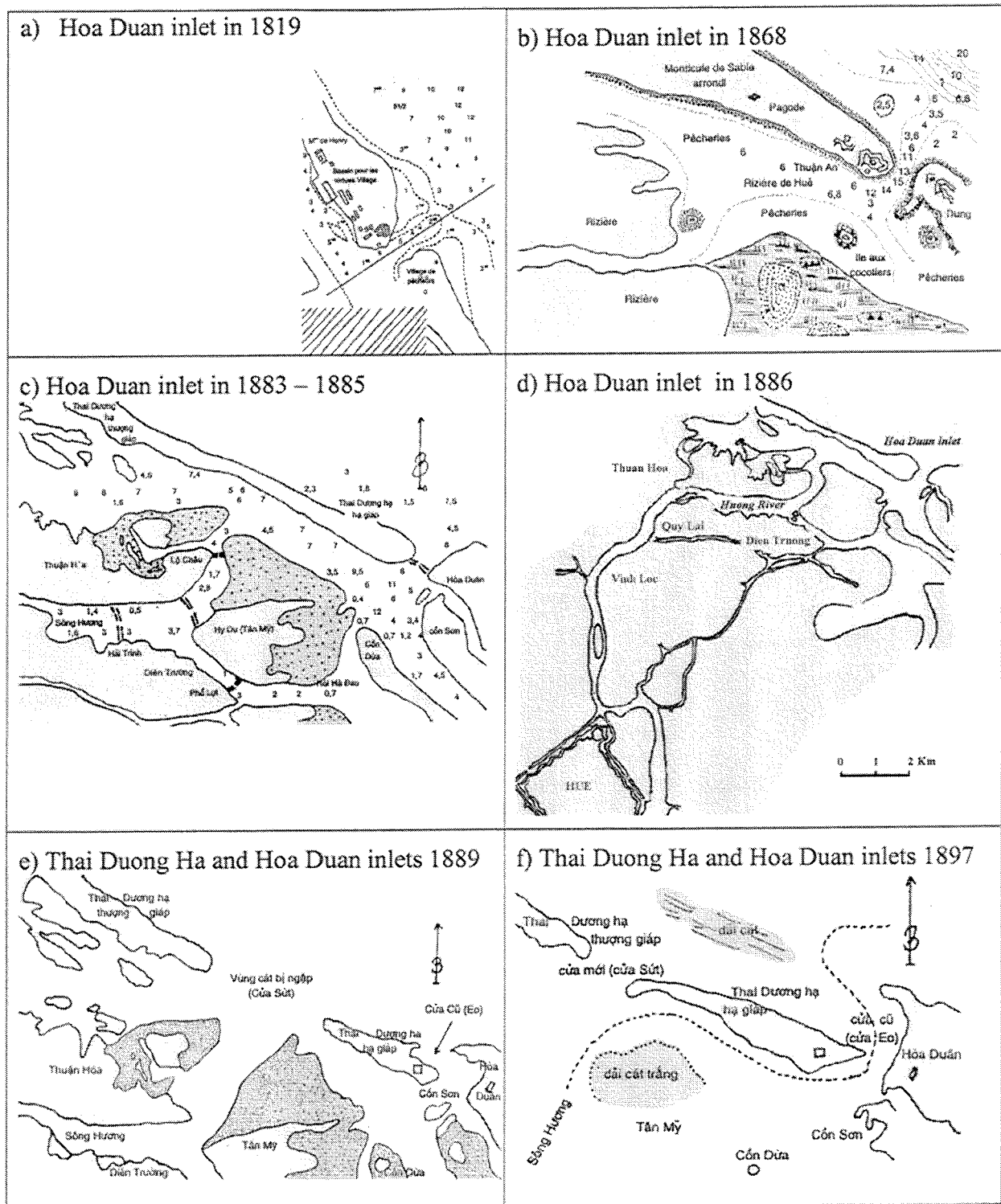


Figure I.4. Configuration of the main inlet at different time periods

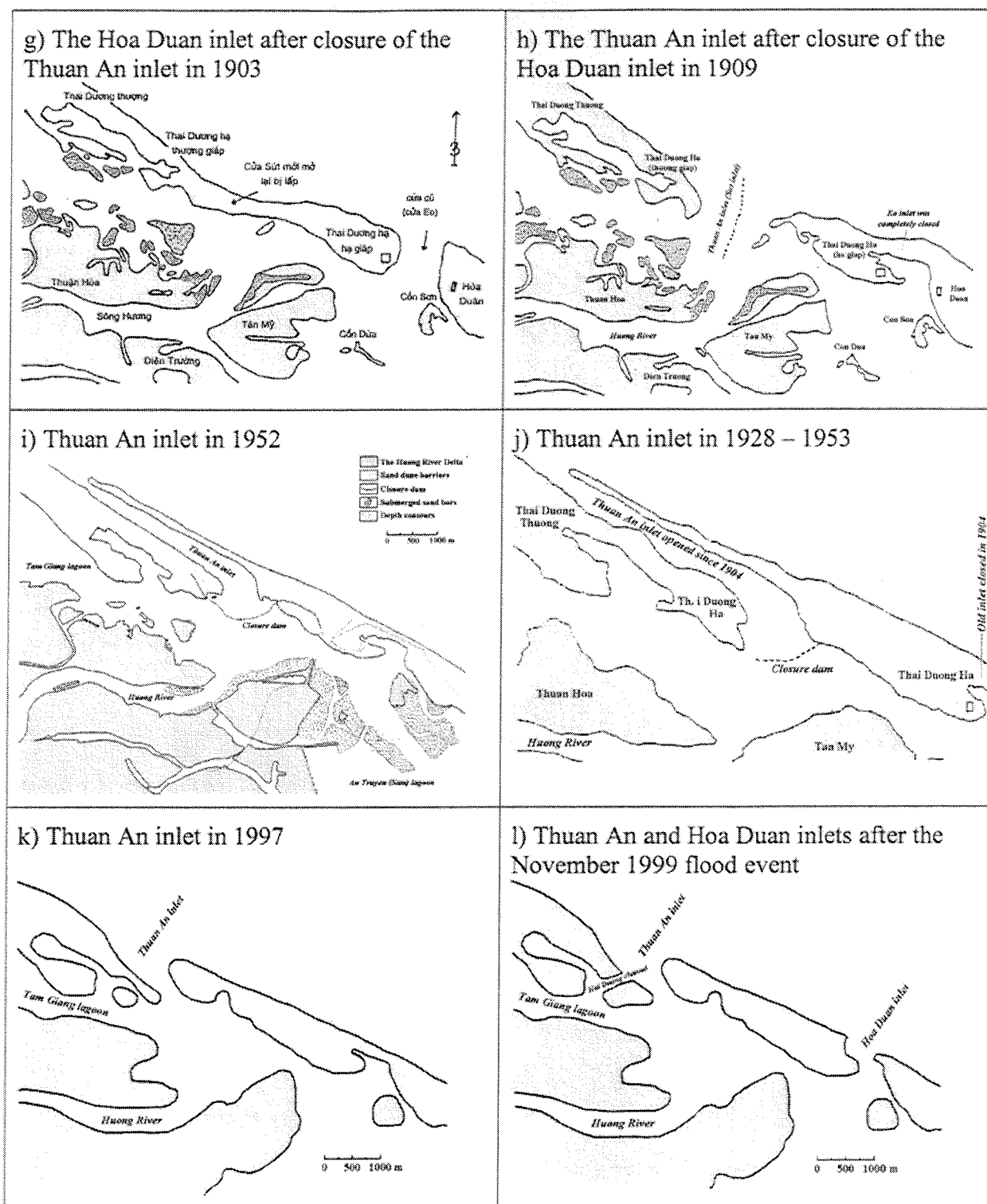


Figure I.4. Configuration of the main inlet at different time periods (continued)

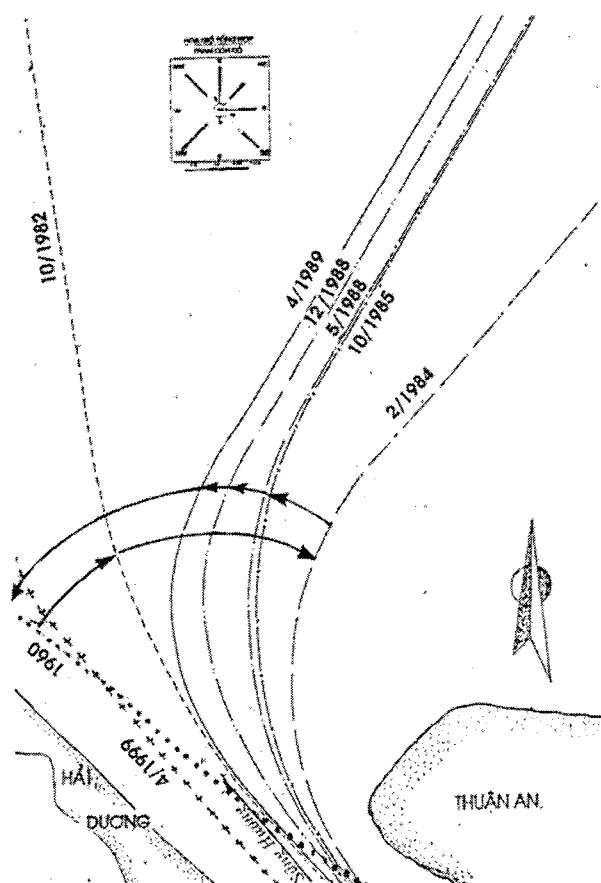


Figure I.5. Movement of the Thuan An inlet channel in the period from 1960 to 1999

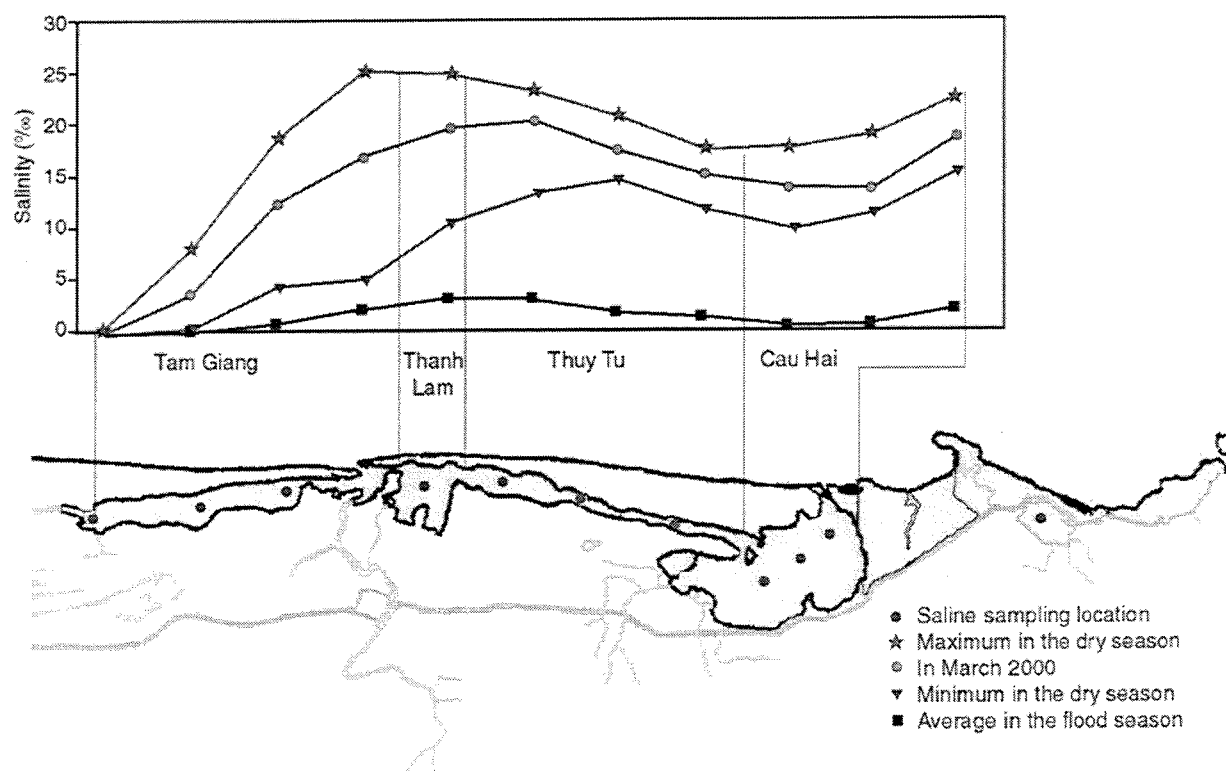


Figure I.6. Variation of salinity in the lagoons in 2000 (after Ton That Phap, 2001)

I.2. TIDAL WATER LEVEL

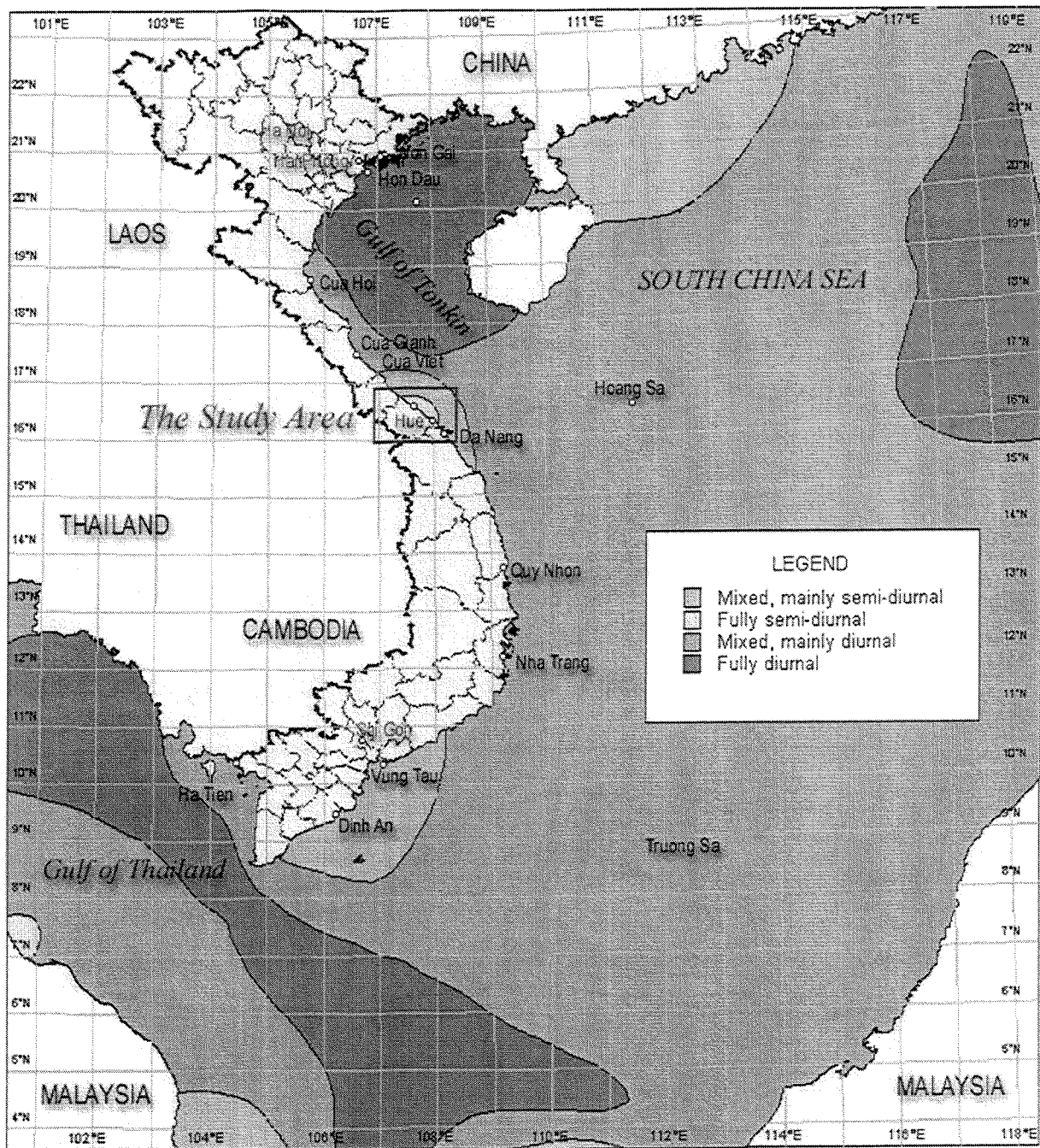


Figure I.7. Tidal Classification for Vietnamese Coast

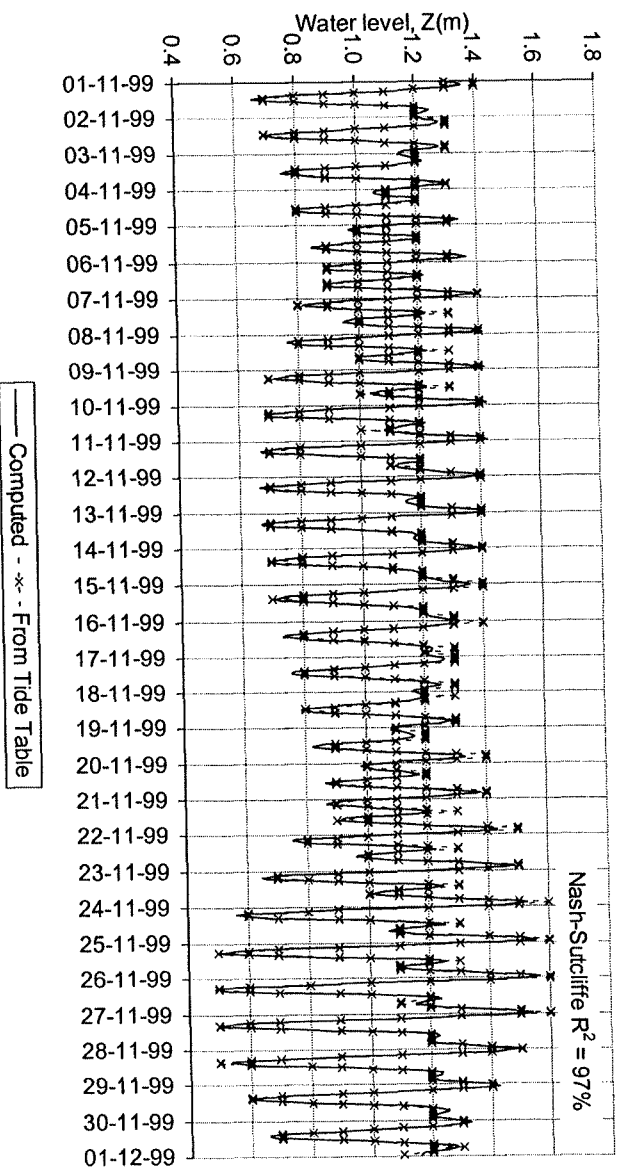


Figure I.8. Astronomic tides in November 1999 at Da Nang station

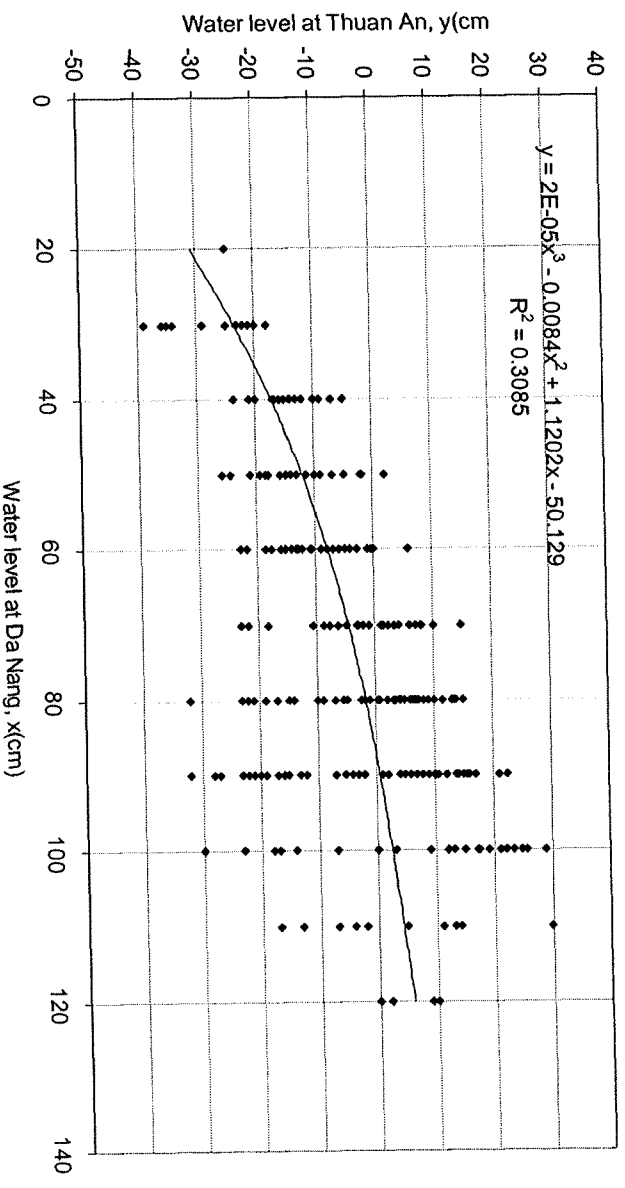


Figure I.9. Relationship of tidal water level Thuan An vs. Da Nang

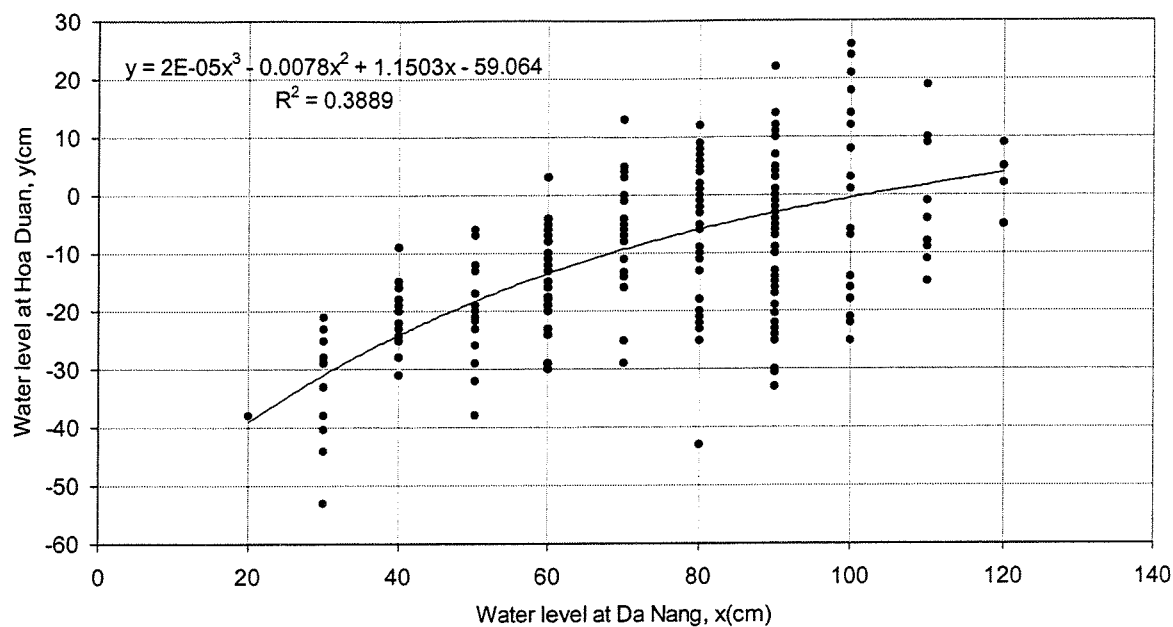


Figure I.10. Relationship of tidal water level Hoa Duan vs. Da Nang

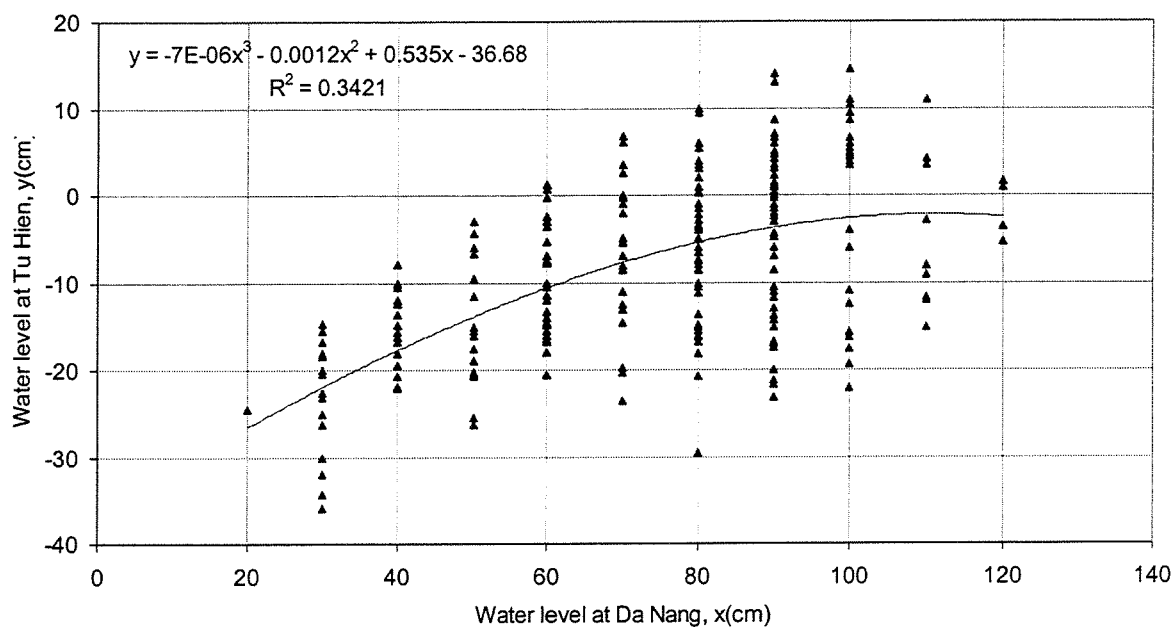


Figure I.11. Relationship of tidal water level Tu Hien vs. Da Nang

I.3. RIVER FLOW DATA

Table I.1. Monthly flow discharges of the rivers

Unit: m³/sSource: VIWRR, 1999^a

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Thuong Nhat	9.88	6.00	4.23	3.91	8.79	9.87	6.29	6.21	15.8	47.6	44.8	25.6
Duong Hoa	35.1	22.8	16.8	10.1	18.8	16.3	9.1	30.9	34.3	114	127	80.4
Binh Dien	28.1	18.9	13.6	12.6	15.9	35.9	15.3	14.6	39.4	134	172	62.1
Co Bi	38.4	24.4	16.2	14.7	20.9	32.2	18.6	20.9	60.3	193	257	89.8
Truoi reservoir	6.67	4.71	2.78	1.57	2.26	1.38	0.829	0.634	7.43	49.3	32.6	30.3

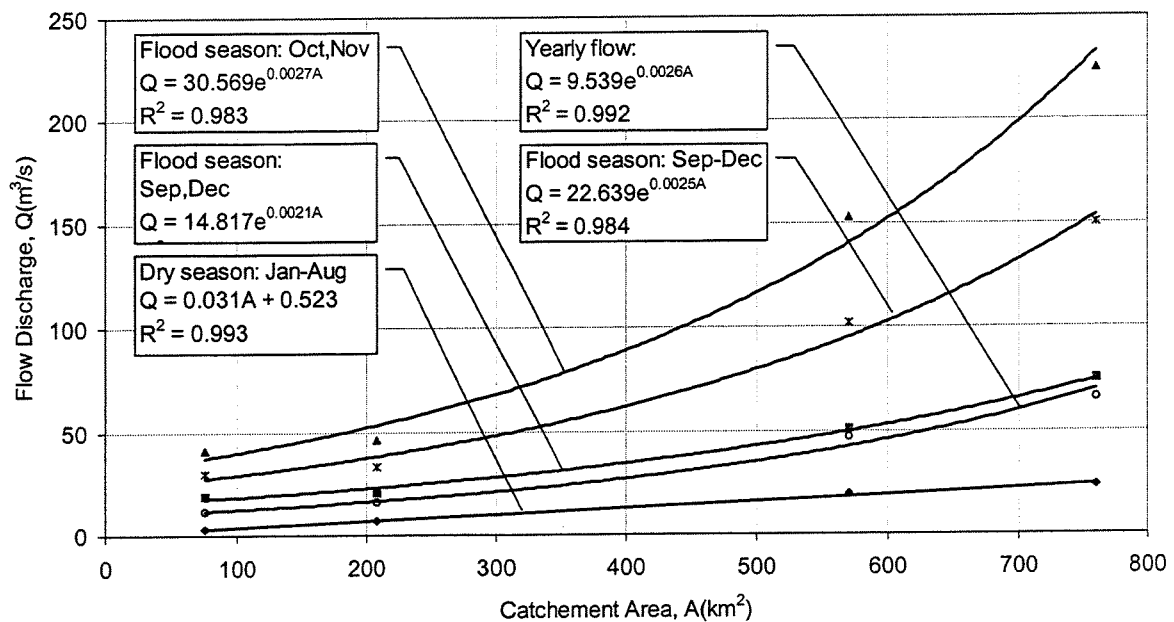


Figure I.12. Relationships of flow discharge and catchment area

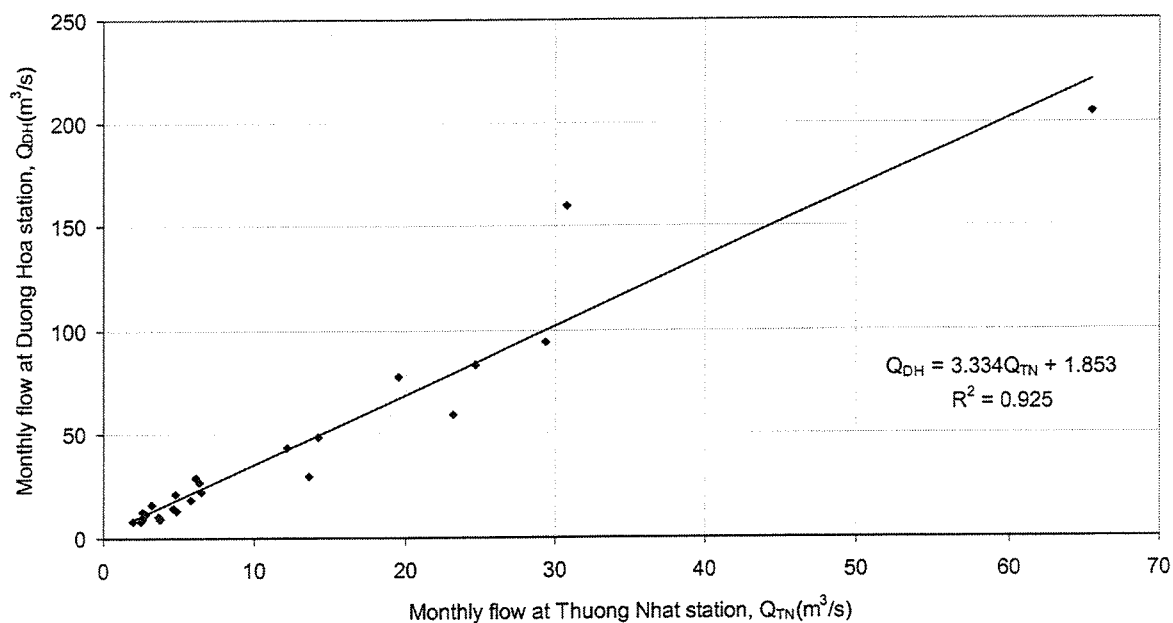


Figure I.13. Relationship of the monthly flows between Thuong Nhat and Duong Hoa

I.4. TOPOGRAPHIC DATA

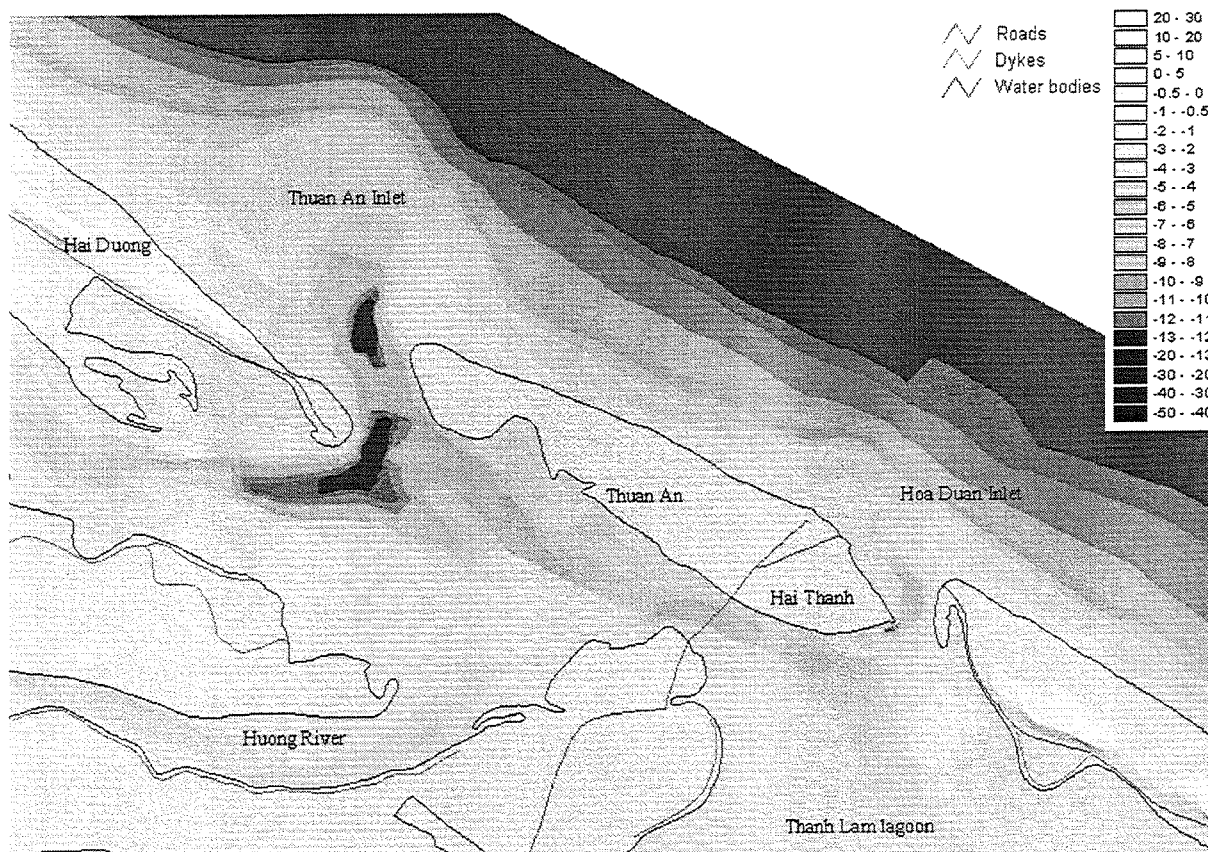


Figure I.14. Topography of Thuan An and Hoa Duan inlets in 2000

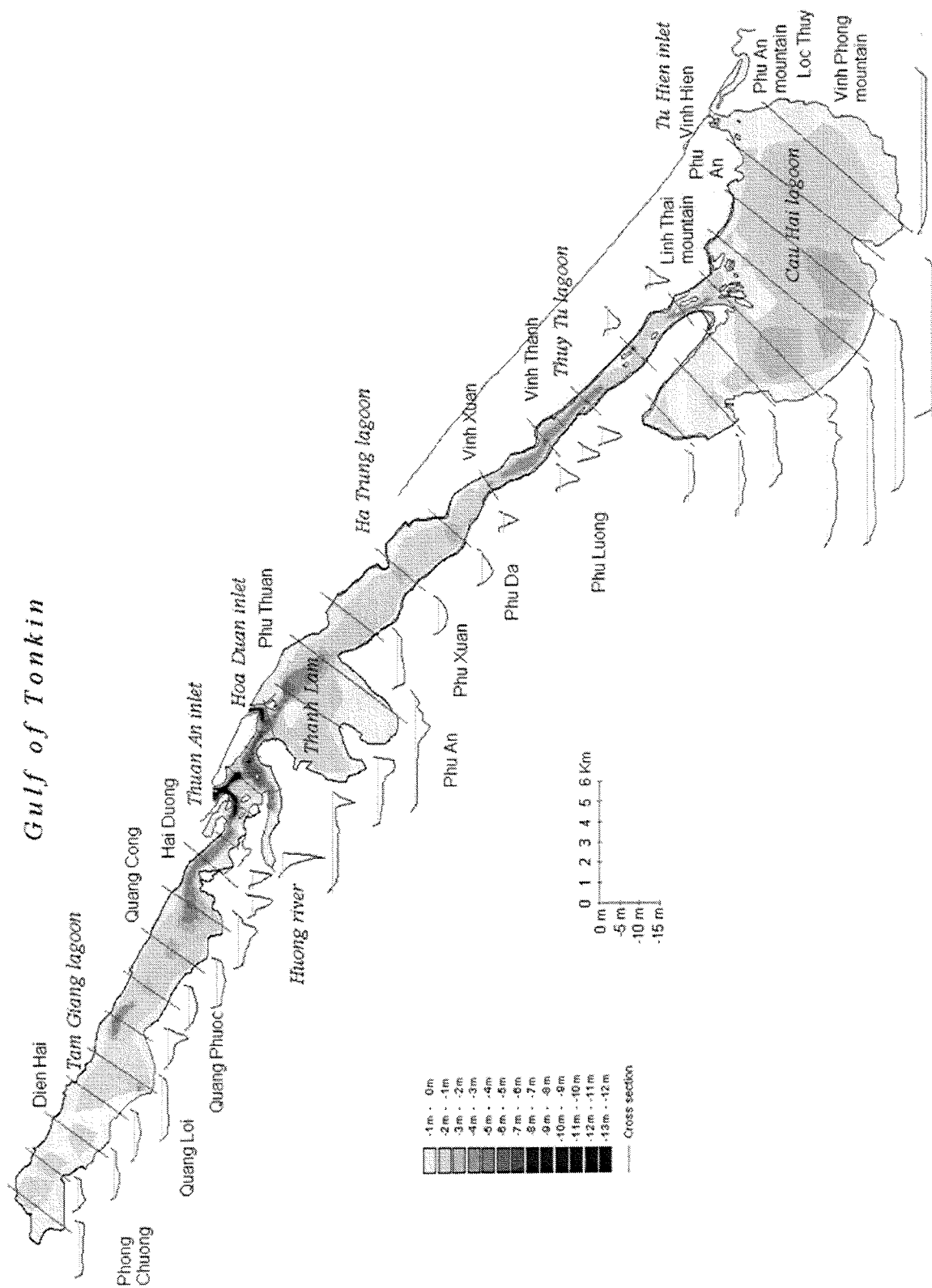


Figure I.15. Topography of the lagoon and its cross sections in 2000

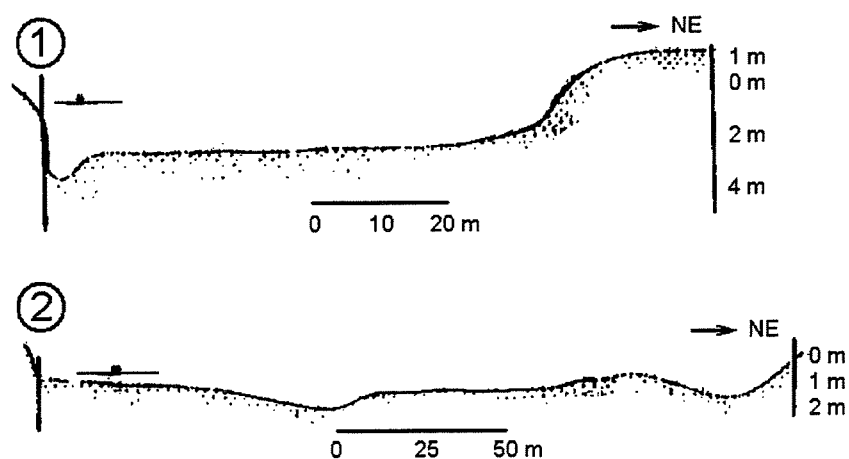


Figure I.16. Cross sections of the Tu Hien inlet in 1993 (Tran Duc Thanh *et al.*, 1996)

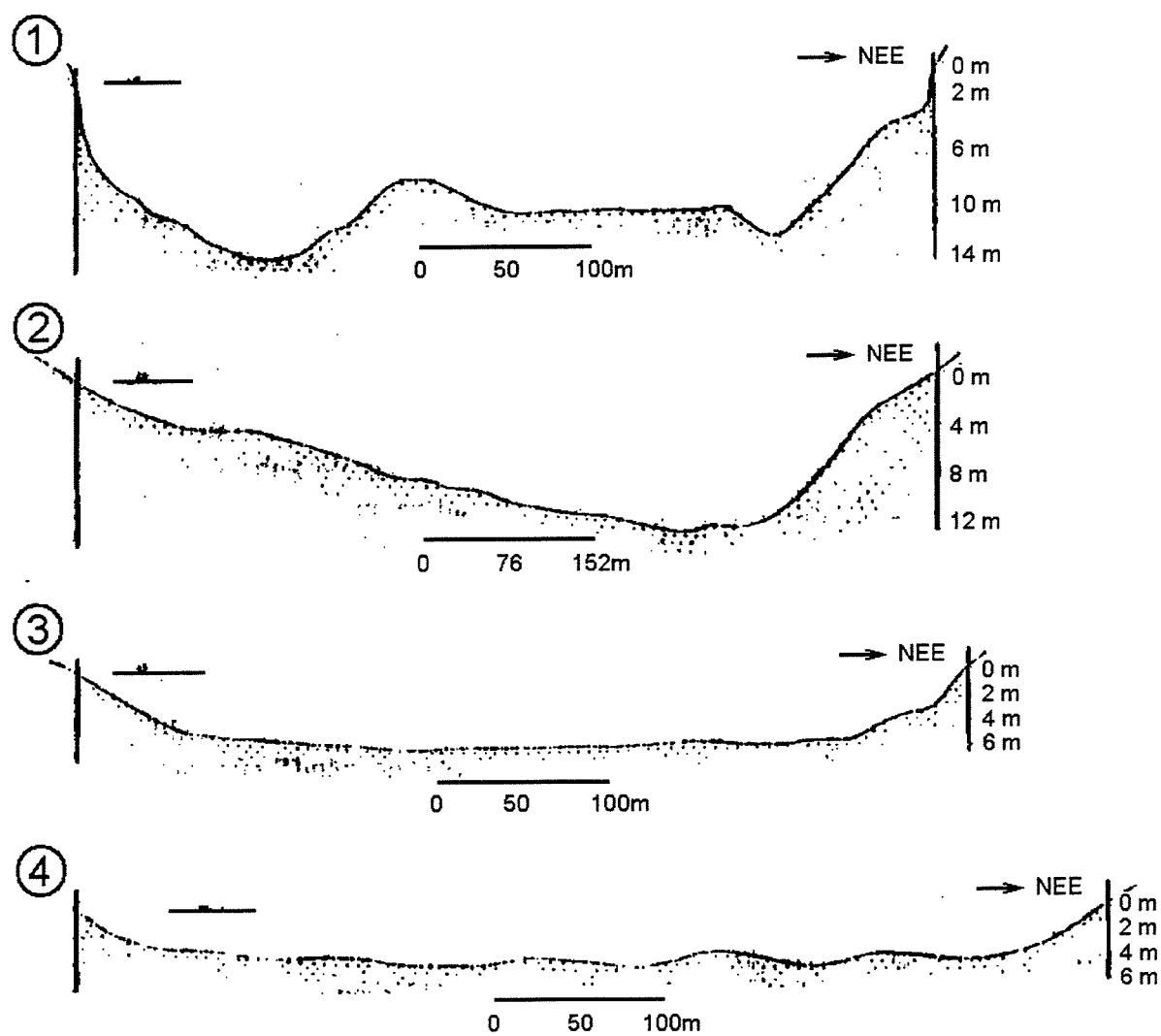


Figure I.17. Cross sections of the Thuan An inlet in 1993 (Tran Duc Thanh *et al.*, 1996)

I.5. SEDIMENTARY DATA

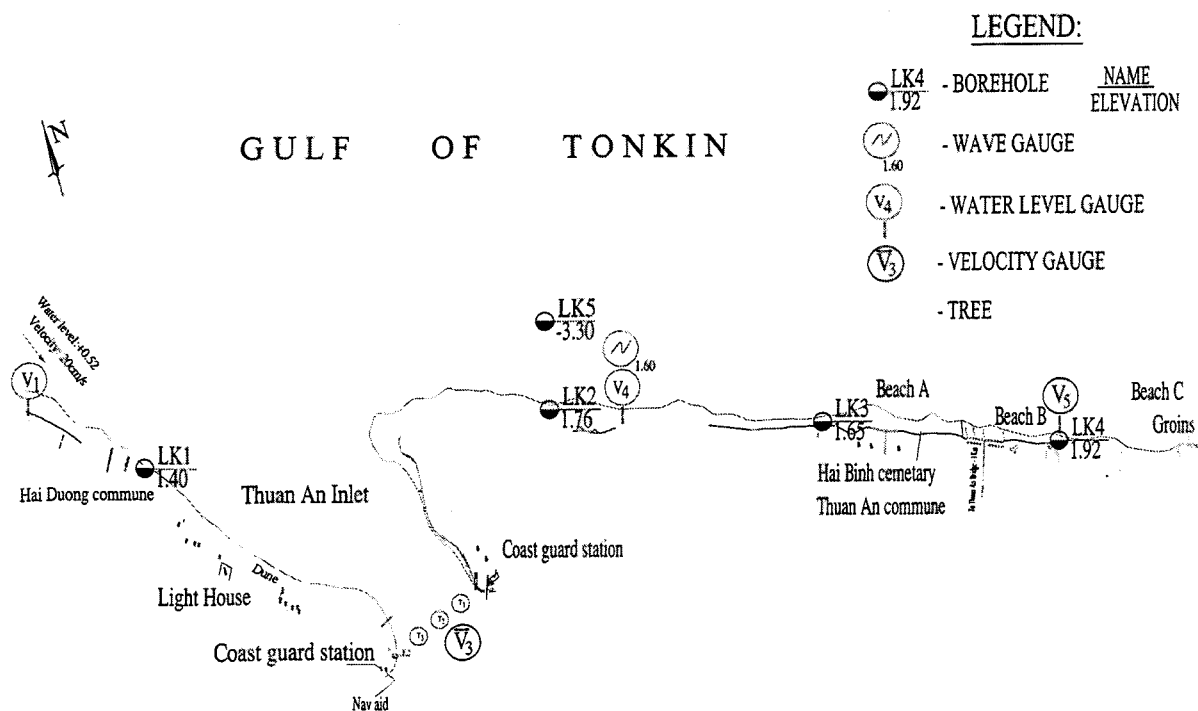


Figure I.18. Bore-holes and gauging locations of the survey in 1999 along the coast from Thuan An to Hoa Duan

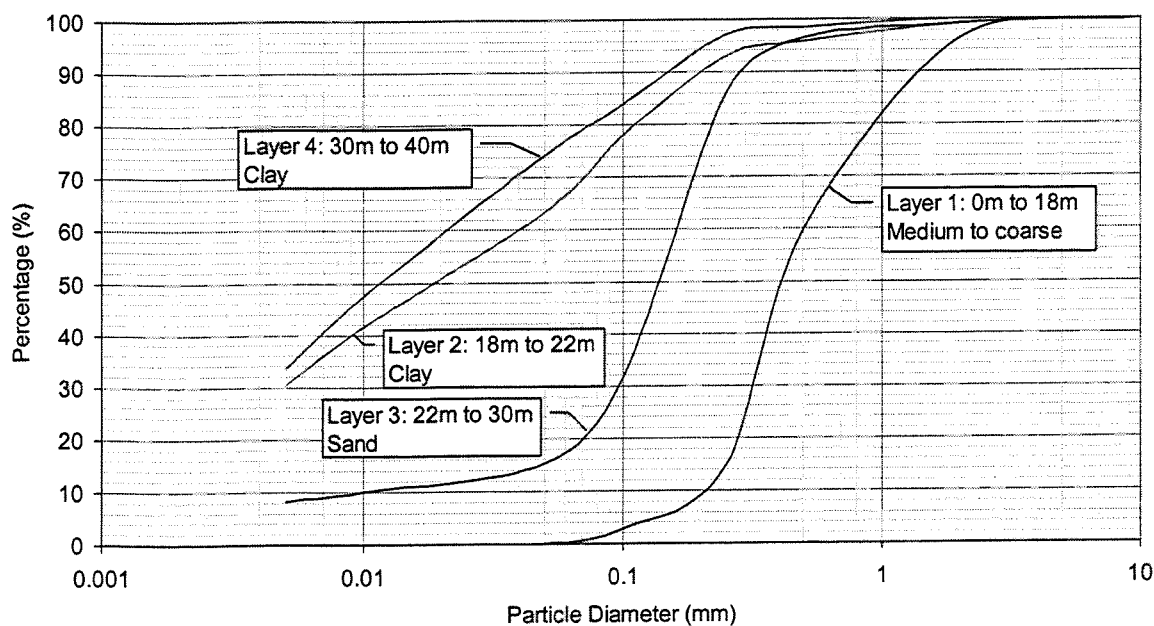


Figure I.19. Grain size distribution of the material along the coastline

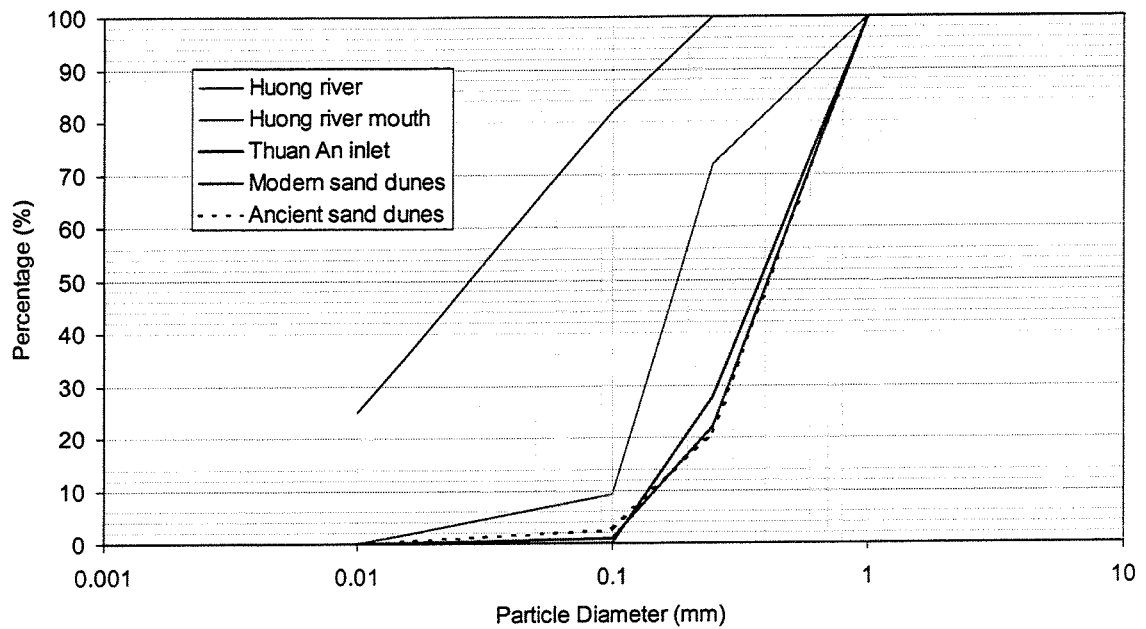


Figure I.20. Grain size distribution of the material at the Thuan An inlet and other locations

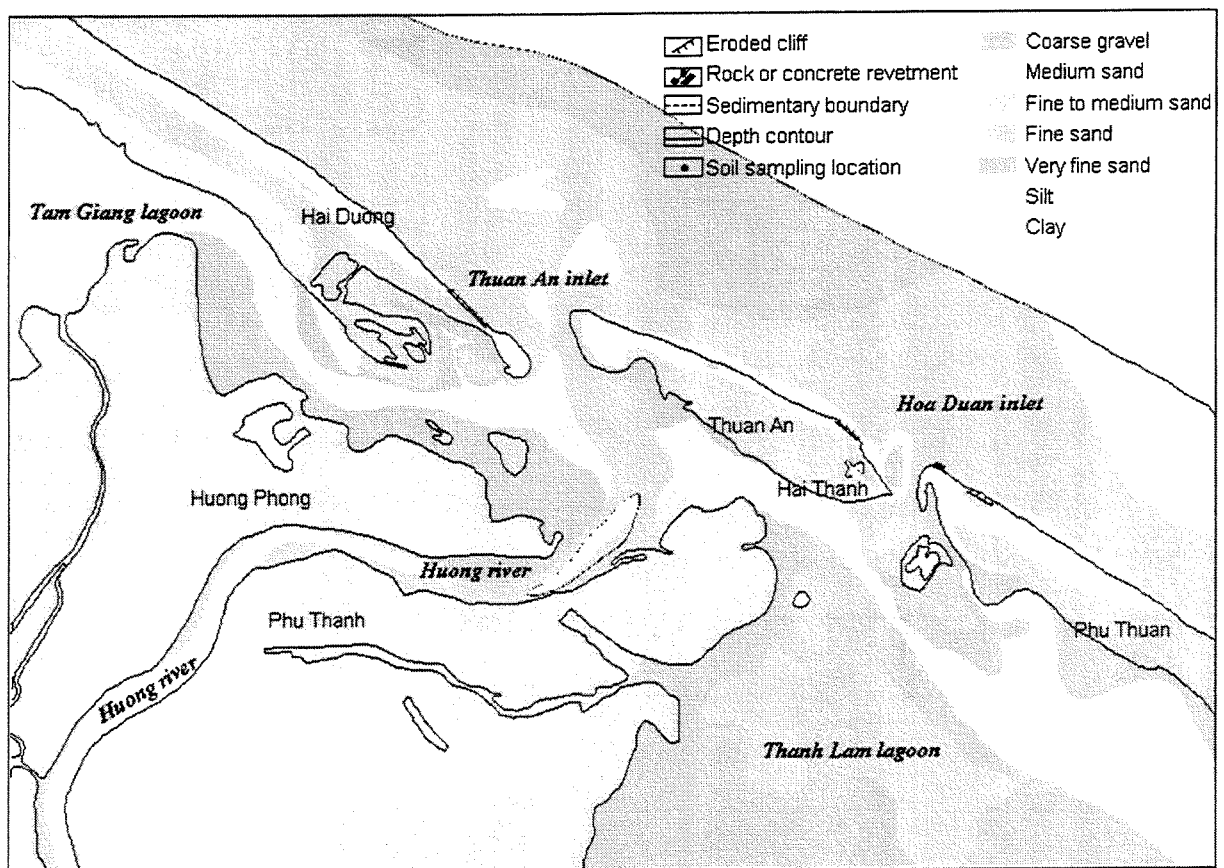


Figure I.21. Sedimentary distribution of the top layer

Appendix II. HYDRAULIC SIMULATION RESULTS

II.1. LIST OF SIMULATIONS AND SCENARIOS

Table II.1. List of the simulations for model calibration

Simulation ID	Description
SD01	Time step $\Delta t = 1$ minutes
SD02	Time step $\Delta t = 5$ minutes
SD03	Time step $\Delta t = 10$ minutes
SD04	Time step $\Delta t = 30$ minutes
SD05	Time step $\Delta t = 60$ minutes
SK01	Bottom roughness $K=30$ ($n=0.033$)
SK02	Bottom roughness $K=40$ ($n=0.025$)
SK03	Bottom roughness $K=50$ ($n=0.020$)
SK04	Bottom roughness $K=55$ ($n=0.018$)
SK05	Bottom roughness $K=60$ ($n=0.017$)
SK06	Bottom roughness $K=70$ ($n=0.014$)
SQ01	Weighting factor Theta, $\theta = 0.90$
SQ02	Weighting factor Theta, $\theta = 0.95$
SQ03	Weighting factor Theta, $\theta = 1.00$

Table II.2. List of the simulations with sea water level at the downstream boundaries

Simulation ID	Description
SZ01	Astronomical Tides
SZ02	Astronomical Tides with mean water level is 0m
SZ03	Tides with only 50% of $H(M_2)$
SZ04	Tides with only 90% of $H(M_2)$
SZ05	Tides with 110% of $H(M_2)$
SZ06	Tides with 150% of $H(M_2)$
SZ07	Constant sea water level $Z = -1\text{m}$
SZ08	Constant sea water level $Z = 0\text{m}$
SZ09	Constant sea water level $Z = 1\text{m}$
SZ10	Constant sea water level $Z = 2\text{m}$
SZ11	Constant sea water level $Z = 3\text{m}$
SZ12	Astronomical Tides + Additional sea level rise 0.1m
SZ13	Astronomical Tides + Additional sea level rise 0.2m
SZ14	Astronomical Tides + Additional sea level rise 0.5m
SZ15	Astronomical Tides + Additional storm surge of 1.0m
SZ16	Astronomical Tides + Additional storm surge of 1.5m
SZ17	Astronomical Tides + Additional storm surge of 2.0m

Table II.3. List of the scenarios for inlet openings

Scenario ID	Thuan An inlet			Hoa Duan inlet			Tu Hien inlet			Year		
	B(m)	d(m)	A(m ²)	B(m)	d(m)	A(m ²)	B(m)	d(m)	A(m ²)	1983	1999	2000
SO01	535	12	4200	420	8	1868	189	6.5	826	☒	☒	☒
SO02	535	12	4200	<i>closed</i>	<i>closed</i>	<i>closed</i>	189	6.5	826			☒
SO03	<i>closed</i>	<i>closed</i>	<i>closed</i>	420	8	1868	189	6.5	826			☒
SO04	344	6	1468	217	4	597	189	6.5	826			☒
SO05	344	6	1468	<i>closed</i>	<i>closed</i>	<i>closed</i>	189	6.5	826			☒
SO06	<i>closed</i>	<i>closed</i>	<i>closed</i>	217	4	597	189	6.5	826			☒
SO07	405	11.5		420	8	1868	189	6.5	826		☒	
SO08	405	11.5		<i>closed</i>	<i>closed</i>	<i>closed</i>	189	6.5	826		☒	
SO09	535	12	4200	420	8	1868	697	1	510	☒		
SO10	535	12	4200	<i>closed</i>	<i>closed</i>	<i>closed</i>	697	1	510	☒		
SO11	344	6	1468	<i>closed</i>	<i>closed</i>	<i>closed</i>	697	1	510	☒		
SO12	535	12	4200	1000	1	1000	697	1	510		☒	
SO13	535	12	4200	1000	0	<i>weir</i>	697	1	510		☒	
SO14	344	6	1468	1000	-1	<i>weir</i>	697	1	510		☒	
SO15	535	12	4200	600	1	1000	697	1	510		☒	
SO16	535	12	4200	600	0	<i>weir</i>	697	1	510		☒	
SO17	344	6	1468	600	-1	<i>weir</i>	697	1	510		☒	

II.2. RESULTS OF MODEL CALIBRATION WITH THE FLOOD EVENT OF OCTOBER 1983

II.2.1. Effect of bottom roughness

Table II.4. Effect of the roughness on the computed $Z_{\max}$ of the flood 1983

Simulation	SK01	SK02	SK03	SK04	SK05	SK06
Roughness K	K=30	K=40	K=50	K=55	K=60	K=70
Manning's roughness n	0.033	0.025	0.020	0.018	0.017	0.014
$Z_{\max}$ (m) Kim long	5.80	5.26	4.88	4.73	4.59	4.37
$Z_{\max}$ (m) Phu Oc	6.31	5.73	5.32	5.16	5.01	4.76

II.2.2. Effect of time step Δt Table II.5. Effect of the roughness on the computed $Z_{\max}$ of the flood 1983

Simulation	SD01	SD02	SD03	SD04	SD05
Time step Δt (minutes)	$\Delta t = 1$ min.	$\Delta t = 5$ min.	$\Delta t = 10$ min.	$\Delta t = 30$ min.	$\Delta t = 60$ min.
$Z_{\max}$ (m) Kim Long	4.74	4.73	4.73	4.73	4.74
$Z_{\max}$ (m) Phu Oc	5.16	5.16	5.16	5.15	5.14

II.2.3. Effect of weighting factor θ Table II.6. Effect of the weighting factor θ on the computed $Z_{\max}$

Simulation	SQ01	SQ02	SQ03
Weighting factor θ	0.90	0.95	1.00
$Z_{\max}$ (m) at Kim Long	4.73	4.73	4.73
$Z_{\max}$ (m) at Phu Oc	5.16	5.16	5.16

II.2.4. Effect of storm surges and downstream water levelsTable II.7. Effect of the sea water level on the computed $Z_{\max}$ of the flood 1983

Sea water level at Thuan An and Tu Hien	Astro. tides	Constant sea water level Z				
		-1 m	0 m	1 m	2 m	3 m
Simulation	SZ01	SZ07	SZ08	SZ09	SZ10	SZ11
$Z_{\max}$ (m) at Kim Long	4.73	4.69	4.69	4.72	4.80	4.97
$Z_{\max}$ (m) at Phu Oc	5.16	5.11	5.12	5.15	5.25	5.39

II.2.5. Effect of inlet openings

Table II.8. Effect of inlet openings on the water level at checkpoints

Inlet openings	$Z_{\max}$ Kim Long (m)	$Z_{\max}$ Phu Oc (m)
SO02: Thuan An: B=535m; Hoa Duan: Closed	4.73	5.16
SO09: Thuan An: B=535m; Hoa Duan: B=420m	4.73	5.16
SO10: Thuan An: B=535m; Hoa Duan: closed	4.73	5.16
SO11: Thuan An: B=344m; Hoa Duan: closed	4.73	5.16

II.3. RESULTS OF MODEL VERIFICATION WITH THE FLOOD EVENT OF NOVEMBER 1999

II.3.1. Effect of storm surges

Table II.9. Effect of storm surges on the maximum flow velocity (m/s) in the lagoons and inlets

Scenario	Phase	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai	Thuan An	Hoa Duan	Tu Hien
SZ01:Only astro. tides	Ebb	0.54	0.54	1.75	0.01	-0.07	-0.23	0.09	2.37	1.77	1.49
	Flood	0.03	-0.08	-0.37	-0.50	-0.32	-0.55	-0.09	0.30	0.10	-1.34
SZ02:Tides with mean WL=0	Ebb	0.59	0.59	1.96	0.23	0.12	0.19	0.13	2.41	1.78	1.91
	Flood	0.05	-0.05	-0.29	-0.41	-0.25	-0.47	-0.05	0.34	0.02	-0.79
SZ14:+Storm surge of 1.0m	Ebb	0.44	0.45	1.46	-0.04	-0.08	-0.22	0.06	2.27	1.72	1.21
	Flood	0.02	-0.07	-0.29	-0.54	-0.33	-0.57	-0.09	0.30	0.15	-1.44
SZ15:+Storm surge of 1.5m	Ebb	0.39	0.42	1.36	-0.05	-0.08	-0.21	0.05	2.22	1.69	1.03
	Flood	0.02	-0.06	-0.24	-0.54	-0.34	-0.57	-0.09	0.29	0.15	-1.49
SZ16:+Storm surge of 2.0m	Ebb	0.35	0.38	1.30	-0.07	-0.05	-0.11	0.04	2.19	1.68	0.80
	Flood	0.02	-0.05	-0.20	-0.54	-0.33	-0.57	-0.09	0.26	0.16	-1.53

Table II.10. Effect of storm surges on the maximum water level (m) in the lagoons

Scenario	Value	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai
SZ01:Only astronomical tides	Max	1.62	1.49	1.04	1.00	1.03	1.24	1.31
	Min	0.44	0.43	0.41	0.49	0.58	0.81	0.87
	Average	1.10	1.02	0.74	0.76	0.82	1.03	1.08
SZ02:Tides with mean WL=0	Max	1.38	1.20	0.51	0.41	0.44	0.60	0.65
	Min	-0.04	-0.09	-0.16	-0.08	-0.03	0.04	0.05
	Average	0.74	0.61	0.18	0.15	0.20	0.28	0.30
SZ14:+Storm surge of 1.0m	Max	2.28	2.22	1.98	1.96	1.99	2.16	2.22
	Min	1.38	1.38	1.40	1.47	1.51	1.74	1.80
	Average	1.87	1.84	1.70	1.72	1.75	1.96	2.00
SZ15:+Storm surge of 1.5m	Max	2.70	2.65	2.47	2.45	2.47	2.64	2.69
	Min	1.88	1.88	1.89	1.96	1.99	2.20	2.24
	Average	2.31	2.29	2.18	2.21	2.23	2.43	2.47
SZ16:+Storm surge of 2.0m	Max	3.14	3.12	2.96	2.94	2.96	3.11	3.16
	Min	2.37	2.37	2.39	2.46	2.48	2.67	2.71
	Average	2.77	2.76	2.68	2.69	2.72	2.91	2.95

Table II.11. Effect of storm surges on the maximum flow discharge (m^3/s) in the lagoons and inlets

Scenario	Phase	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai	Thuan An	Hoa Duan	Tu Hien
SZ01:Only astro. tides	Ebb	3088	3169	4366	-6	-640	-834	1646	9916	3768	1645
	Flood	180	-279	-870	-2331	-2200	-2158	-1297	1300	217	-1606
SZ02:Tides with mean WL=0	Ebb	3089	3109	4224	924	676	528	1856	9446	3340	1623
	Flood	163	-113	-588	-1565	-1345	-1402	-275	1383	37	-714
SZ14:+Storm surge of 1.0m	Ebb	3109	3291	4665	-338	-884	-1061	1499	10598	4449	1685
	Flood	180	-385	-916	-3322	-3070	-2923	-1806	1415	397	-2170
SZ15:+Storm surge of 1.5m	Ebb	3123	3359	4863	-489	-980	-1171	1310	10948	4805	1590
	Flood	178	-383	-889	-3783	-3505	-3316	-2064	1442	438	-2463
SZ16:+Storm surge of 2.0m	Ebb	3133	3404	5191	-641	-610	-639	1034	11365	5171	1350
	Flood	178	-371	-802	-4177	-3902	-3704	-2358	1367	495	-2765

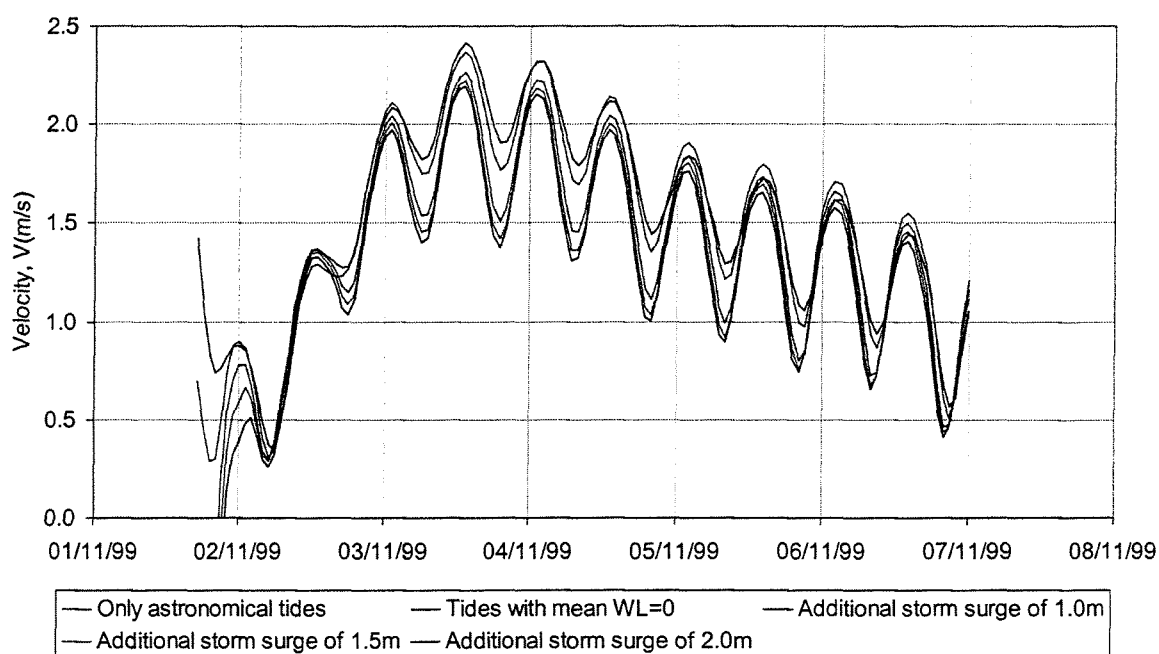


Figure II.1. Effect of storm surges on the maximum flow velocity at the Thuan An inlet during the Flood of November 1999

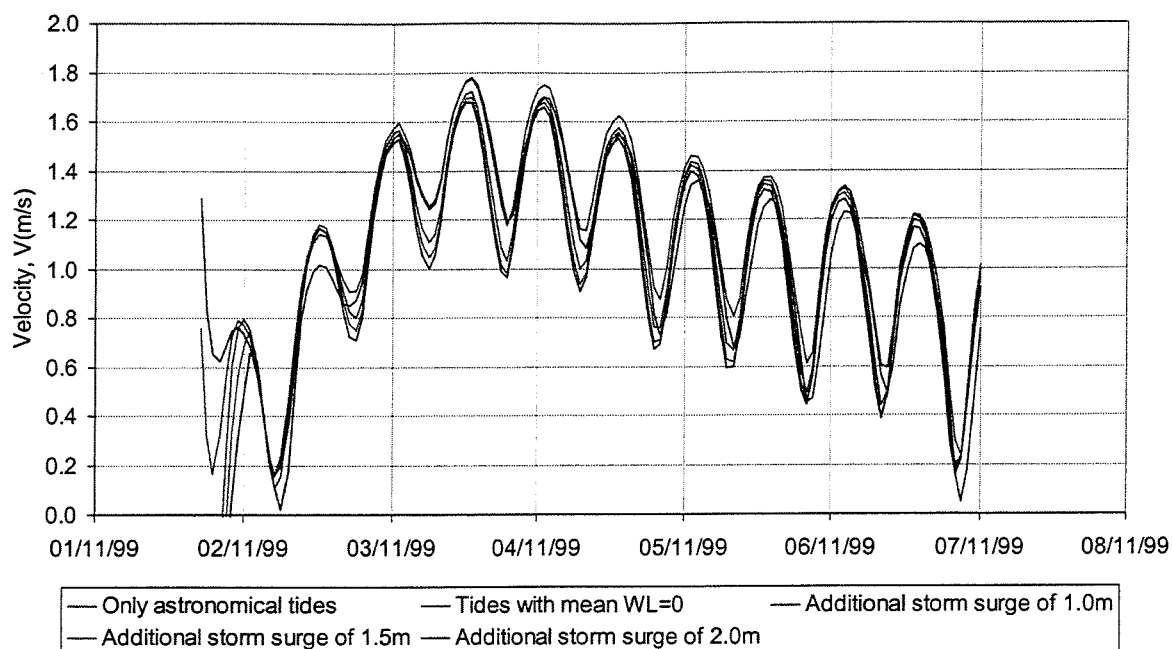


Figure II.2. Effect of storm surges on the maximum flow velocity at the Hoa Duan inlet during the Flood of November 1999

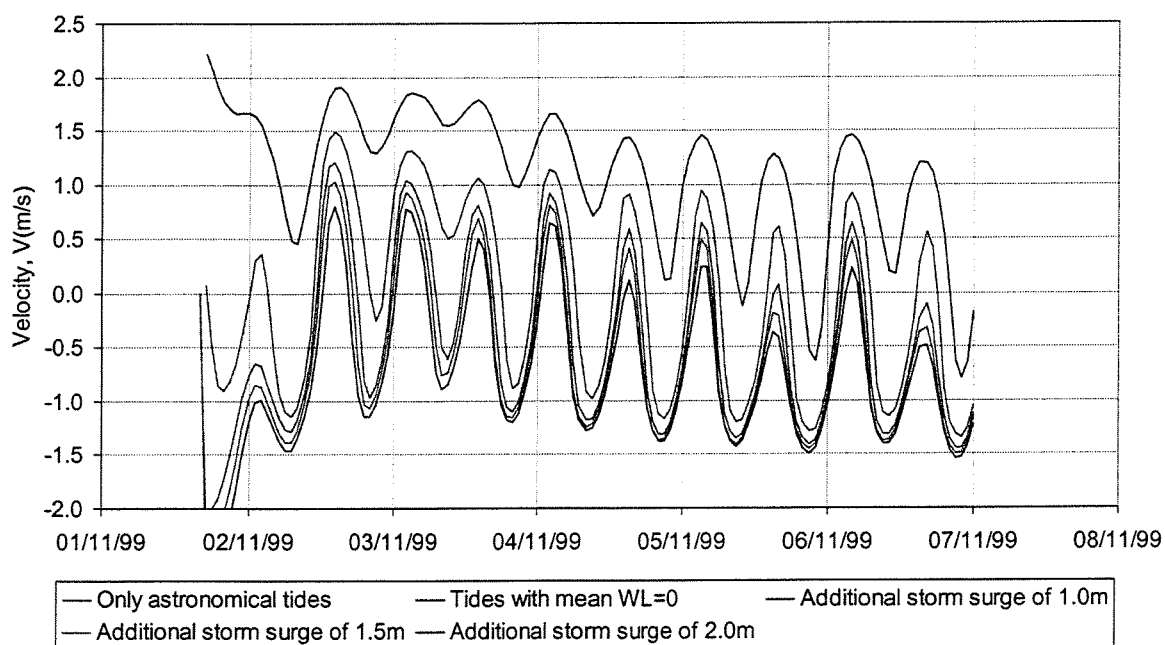


Figure II.3. Effect of storm surges on the maximum flow velocity at the Tu Hien inlet during the Flood of November 1999

II.3.2. Effect of inlet openings

Table II.12. Effect of inlet openings on the maximum flow velocity (m/s) in the system

Scenario	Phase	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai	Thuan An	Hoa Duan	Tu Hien
SO01: TA: B=535m; HD: B=420m	Ebb	0.54	0.54	1.75	0.01	-0.07	-0.23	0.09	2.37	1.77	1.49
	Flood	0.03	-0.08	-0.37	-0.50	-0.32	-0.55	-0.09	0.30	0.10	-1.34
SO07: TA: B=405m; Hoa Duan: B=420m	Ebb	0.54	0.54	1.72	0.01	-0.07	-0.23	0.09	2.75	1.93	1.49
	Flood	0.03	-0.07	-0.36	-0.50	-0.32	-0.55	-0.09	0.36	0.13	-1.33
SO08: TA: B=405m; Hoa Duan: closed	Ebb	0.52	0.51	1.60	-0.01	-0.04	-0.16	0.09	3.68		1.53
	Flood	0.03	-0.05	-0.29	-0.41	-0.28	-0.50	-0.08	0.54		-1.28
SO12: HD weir: Z=-1m, B=1000m	Ebb	0.39	0.41	1.34	-0.06	-0.08	-0.22	0.05	2.42	1.18	1.04
	Flood	0.02	-0.06	-0.23	-0.53	-0.33	-0.56	-0.09	0.33	0.08	-1.49
SO13: HD weir: Z=0m, B=1000m	Ebb	0.39	0.41	1.33	-0.06	-0.08	-0.21	0.05	2.66	1.03	1.06
	Flood	0.02	-0.06	-0.22	-0.51	-0.32	-0.54	-0.09	0.36	0.06	-1.48
SO14: HD weir: Z=1m, B=1000m	Ebb	0.38	0.40	1.31	-0.06	-0.08	-0.18	0.06	2.86	0.74	1.09
	Flood	0.02	-0.05	-0.21	-0.48	-0.30	-0.53	-0.08	0.40	0.04	-1.47
SO15: HD weir: Z=-1m, B=600m	Ebb	0.39	0.41	1.33	-0.05	-0.08	-0.21	0.05	2.62	1.31	1.06
	Flood	0.02	-0.06	-0.22	-0.51	-0.32	-0.55	-0.09	0.35	0.10	-1.48
SO16: HD weir: Z=+0m, B=600m	Ebb	0.38	0.40	1.32	-0.05	-0.08	-0.21	0.06	2.78	1.10	1.08
	Flood	0.02	-0.05	-0.22	-0.50	-0.31	-0.53	-0.08	0.38	0.07	-1.47
SO17: HD weir: Z=+1m, B=600m	Ebb	0.38	0.40	1.31	-0.06	-0.08	-0.17	0.06	2.91	0.76	1.09
	Flood	0.02	-0.05	-0.21	-0.48	-0.30	-0.52	-0.08	0.40	0.04	-1.47

Table II.13. Effect of inlet openings on the maximum flow discharge (m³/s) in the system

Scenario	Phase	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai	Thuan An	Hoa Duan	Tu Hien
SO01: TA: B=535m; HD: B=420m	Ebb	3088	3169	4366	-6	-640	-834	1646	9916	3768	1645
	Flood	180	-279	-870	-2331	-2200	-2158	-1297	1300	217	-1606
SO07: TA: B=405m; Hoa Duan: B=420m	Ebb	3087	3166	4358	-35	-642	-833	1648	9480	4113	1646
	Flood	179	-262	-849	-2321	-2192	-2151	-1291	1279	282	-1599
SO08: TA: B=405m; Hoa Duan: closed	Ebb	3084	3144	4302	-109	-399	-597	1762	12878		1695
	Flood	160	-157	-703	-2064	-2020	-2002	-1256	1931		-1542
SO12: HD weir: Z=-1m, B=1000m	Ebb	3119	3345	4830	-501	-998	-1192	1334	11960	3737	1609
	Flood	176	-369	-857	-3716	-3449	-3267	-2064	1642	255	-2457
SO13: HD weir: Z=0m, B=1000m	Ebb	3116	3334	4811	-500	-997	-1197	1373	13153	2341	1641
	Flood	173	-343	-801	-3613	-3361	-3188	-2065	1818	126	-2448
SO14: HD weir: Z=1m, B=1000m	Ebb	3113	3323	4800	-511	-980	-969	1421	14191	1038	1681
	Flood	170	-309	-753	-3485	-3252	-3090	-2064	1989	30	-2436
SO15: HD weir: Z=-1m, B=600m	Ebb	3117	3338	4821	-486	-987	-1190	1364	12945	2524	1635
	Flood	174	-348	-813	-3643	-3384	-3207	-2066	1762	180	-2451
SO16: HD weir: Z=+0m, B=600m	Ebb	3114	3330	4811	-497	-981	-1118	1398	13765	1520	1663
	Flood	171	-325	-766	-3551	-3306	-3137	-2065	1906	89	-2442
SO17: HD weir: Z=+1m, B=600m	Ebb	3113	3322	4803	-487	-964	-905	1433	14445	649	1692
	Flood	169	-300	-748	-3458	-3226	-3066	-2063	2032	22	-2433

Table II.14. Effect of inlet openings on the maximum water level (m) in the system

Scenario	Water level (m) in the lagoons							Water level (m) at the inlets			Difference in water level (m)		
	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai	Thuan An	Hoa Duan	Tu Hien	Tam Giang – Cau Hai	Tam Giang – Thuan An	Cau Hai – Tu Hien
SO01	1.62	1.49	1.04	1.00	1.03	1.24	1.31	0.89	0.90	1.29	0.34	0.94	0.29
SO07	1.64	1.52	1.08	1.02	1.05	1.25	1.31	0.89	0.90	1.29	0.36	0.97	0.29
SO08	1.74	1.63	1.23	1.23	1.25	1.35	1.38	0.92	1.21	1.30	0.38	1.04	0.31
SO12	2.71	2.66	2.48	2.47	2.49	2.65	2.70	2.39	2.40	2.79	0.66	0.49	0.16
SO13	2.73	2.69	2.50	2.50	2.52	2.67	2.71	2.39	2.41	2.79	0.65	0.51	0.16
SO14	2.75	2.71	2.53	2.53	2.55	2.69	2.73	2.39	2.43	2.79	0.64	0.53	0.17
SO15	2.73	2.69	2.50	2.50	2.51	2.67	2.71	2.39	2.40	2.79	0.65	0.51	0.16
SO16	2.74	2.70	2.52	2.52	2.54	2.68	2.72	2.39	2.42	2.79	0.64	0.53	0.17
SO17	2.76	2.72	2.54	2.55	2.57	2.70	2.73	2.39	2.44	2.79	0.64	0.54	0.17

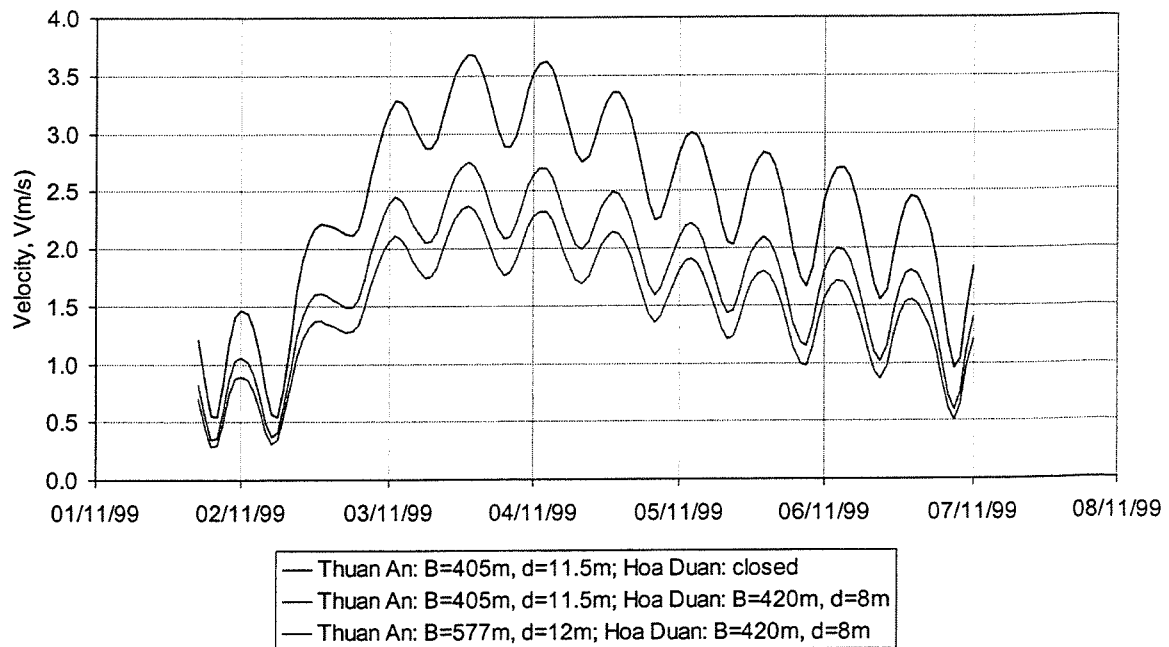


Figure II.4. Effect of inlet openings on the maximum flow velocity at the Thuan An inlet during the Flood of November 1999

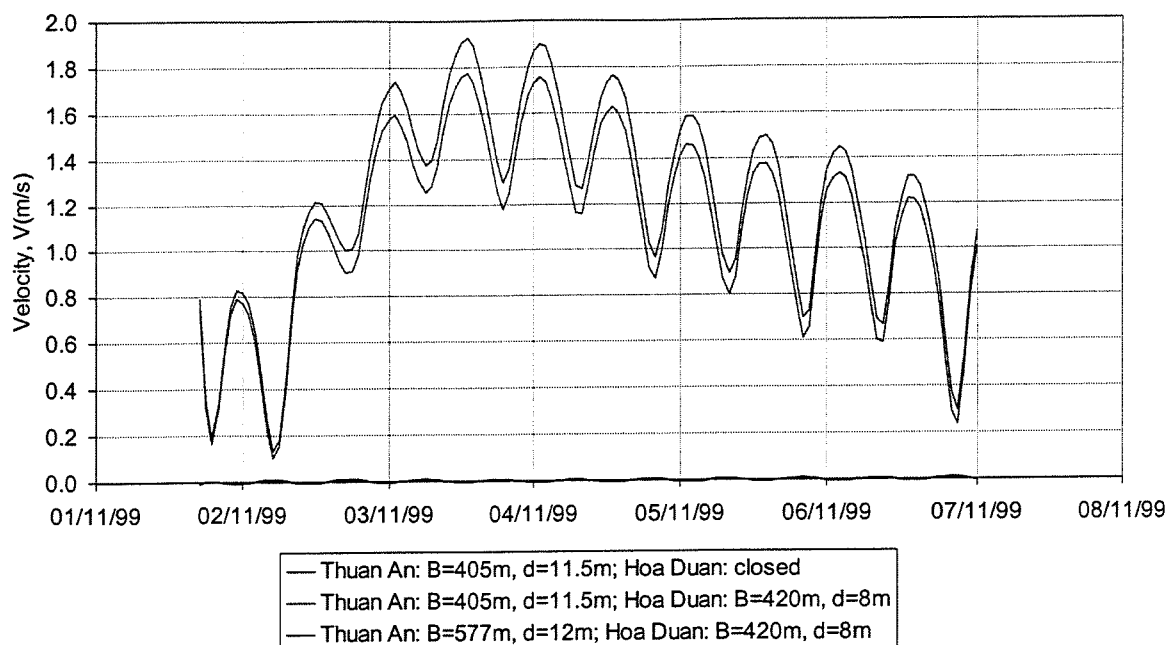


Figure II.5. Effect of inlet openings on the maximum flow velocity at the Hoa Duan inlet during the Flood of November 1999

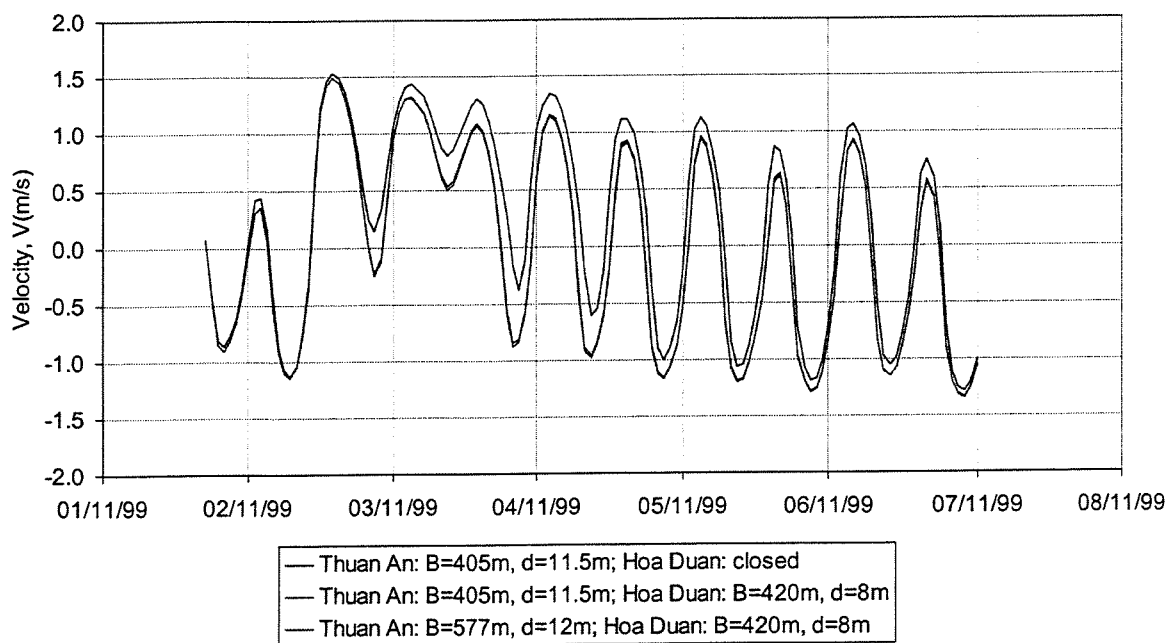


Figure II.6. Effect of inlet openings on the maximum flow velocity at the Tu Hien inlet during the Flood of November 1999

II.4. RESULTS OF MODEL SIMULATION FOR THE DRY SEASON

II.4.1. Effects of the M_2 tidal parameter

Table II.15. Effect of the M_2 tidal parameter on the maximum flow velocity (m/s) in the lagoons and inlets

Scenario	Phase	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai	Thuan An	Hoa Duan	Tu Hien
SZ01: Astro. tides	Ebb	0.03	0.19	0.74	0.29	0.16	0.27	0.08	0.60	0.60	1.09
	Flood	-0.02	-0.21	-0.67	-0.25	-0.14	-0.18	-0.07	-0.59	-0.60	-0.84
SZ03: Tides with 50% of $H(M_2)$	Ebb	0.03	0.18	0.65	0.25	0.15	0.25	0.07	0.52	0.51	0.93
	Flood	-0.01	-0.19	-0.61	-0.22	-0.13	-0.18	-0.05	-0.51	-0.55	-0.71
SZ04: Tides with 90% of $H(M_2)$	Ebb	0.03	0.19	0.72	0.28	0.16	0.26	0.08	0.59	0.59	1.06
	Flood	-0.02	-0.21	-0.66	-0.24	-0.14	-0.18	-0.07	-0.57	-0.59	-0.81
SZ05: Tides with 110% of $H(M_2)$	Ebb	0.03	0.20	0.75	0.29	0.16	0.27	0.08	0.62	0.62	1.12
	Flood	-0.02	-0.22	-0.68	-0.25	-0.14	-0.19	-0.07	-0.61	-0.61	-0.87
SZ06: Tides with 150% of $H(M_2)$	Ebb	0.03	0.21	0.82	0.32	0.18	0.28	0.09	0.68	0.68	1.23
	Flood	-0.02	-0.24	-0.74	-0.28	-0.15	-0.19	-0.08	-0.67	-0.66	-0.99

Table II.16. Effect of the M_2 tidal parameter on the maximum water level (m) in the lagoons

Scenario	Value	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai
SZ01: Astronomical tides	Max	0.34	0.33	0.31	0.27	0.23	0.12	0.08
	Min	-0.31	-0.30	-0.33	-0.29	-0.21	-0.18	-0.17
	Average	-0.01	-0.01	-0.02	-0.02	-0.02	-0.04	-0.04
SZ03: Tides with 50% of $H(M_2)$	Max	0.30	0.29	0.26	0.23	0.19	0.09	0.07
	Min	-0.28	-0.28	-0.29	-0.26	-0.19	-0.17	-0.17
	Average	-0.01	-0.01	-0.02	-0.02	-0.03	-0.04	-0.05
SZ04: Tides with 90% of $H(M_2)$	Max	0.33	0.32	0.30	0.26	0.22	0.12	0.08
	Min	-0.30	-0.29	-0.33	-0.29	-0.20	-0.17	-0.17
	Average	-0.01	-0.01	-0.02	-0.02	-0.02	-0.04	-0.04
SZ05: Tides with 110% of $H(M_2)$	Max	0.35	0.33	0.32	0.28	0.23	0.13	0.09
	Min	-0.31	-0.30	-0.34	-0.30	-0.21	-0.18	-0.17
	Average	-0.01	-0.01	-0.02	-0.02	-0.02	-0.04	-0.04
SZ06: Tides with 150% of $H(M_2)$	Max	0.38	0.36	0.36	0.32	0.26	0.15	0.10
	Min	-0.33	-0.32	-0.38	-0.34	-0.22	-0.18	-0.17
	Average	0.00	-0.01	-0.02	-0.02	-0.02	-0.03	-0.04

Table II.17. Effect of the M2 tidal parameter on the maximum water level (m) at the inlets

Scenario	Value	Water level (m) at inlets			Difference in water level (m)		
		Thuan An	Hoa Duan	Tu Hien	Tam Giang – Cau Hai	Tam Giang – Thuan An	Cau Hai – Tu Hien
SZ01: Astronomical tides	Max	0.32	0.32	0.09	0.26	0.27	0.20
	Min	-0.34	-0.34	-0.22	-0.18	-0.25	-0.14
	Average	-0.02	-0.02	-0.06	0.03	0.01	0.02
SZ03: Tides with 50% of $H(M_2)$	Max	0.27	0.27	0.07	0.24	0.21	0.15
	Min	-0.29	-0.29	-0.18	-0.16	-0.21	-0.09
	Average	-0.02	-0.02	-0.06	0.03	0.01	0.02
SZ04: Tides with 90% of $H(M_2)$	Max	0.31	0.31	0.08	0.26	0.26	0.19
	Min	-0.33	-0.33	-0.21	-0.18	-0.24	-0.12
	Average	-0.02	-0.02	-0.06	0.03	0.01	0.02
SZ05: Tides with 110% of $H(M_2)$	Max	0.33	0.32	0.10	0.27	0.28	0.21
	Min	-0.35	-0.35	-0.23	-0.18	-0.26	-0.15
	Average	-0.02	-0.02	-0.06	0.03	0.01	0.02
SZ06: Tides with 150% of $H(M_2)$	Max	0.37	0.36	0.14	0.29	0.33	0.26
	Min	-0.39	-0.39	-0.26	-0.20	-0.29	-0.19
	Average	-0.02	-0.02	-0.06	0.03	0.01	0.02

Table II.18. Effect of the M2 tidal parameter on the maximum flow discharge (m^3/s) in the lagoons and inlets in the dry season from January to August

Scenario	Phase	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai	Thuan An	Hoa Duan	Tu Hien
SZ01: Astro. tides	Ebb	125	552	1331	1166	840	679	715	2335	1121	860
	Flood	-100	-599	-1339	-828	-590	-444	-542	-2402	-1171	-718
SZ03: Tides with 50% of $H(M_2)$	Ebb	113	495	1179	1004	757	635	625	2013	957	743
	Flood	-87	-534	-1186	-748	-551	-426	-385	-2075	-1061	-606
SZ04: Tides with 90% of $H(M_2)$	Ebb	123	540	1298	1134	824	668	696	2270	1092	839
	Flood	-97	-583	-1304	-812	-580	-440	-518	-2325	-1143	-689
SZ05: Tides with 110% of $H(M_2)$	Ebb	127	564	1363	1195	856	689	731	2393	1151	881
	Flood	-103	-614	-1372	-847	-600	-448	-566	-2472	-1197	-748
SZ06: Tides with 150% of $H(M_2)$	Ebb	135	608	1483	1317	920	730	788	2624	1249	960
	Flood	-116	-679	-1504	-920	-637	-463	-646	-2750	-1298	-861

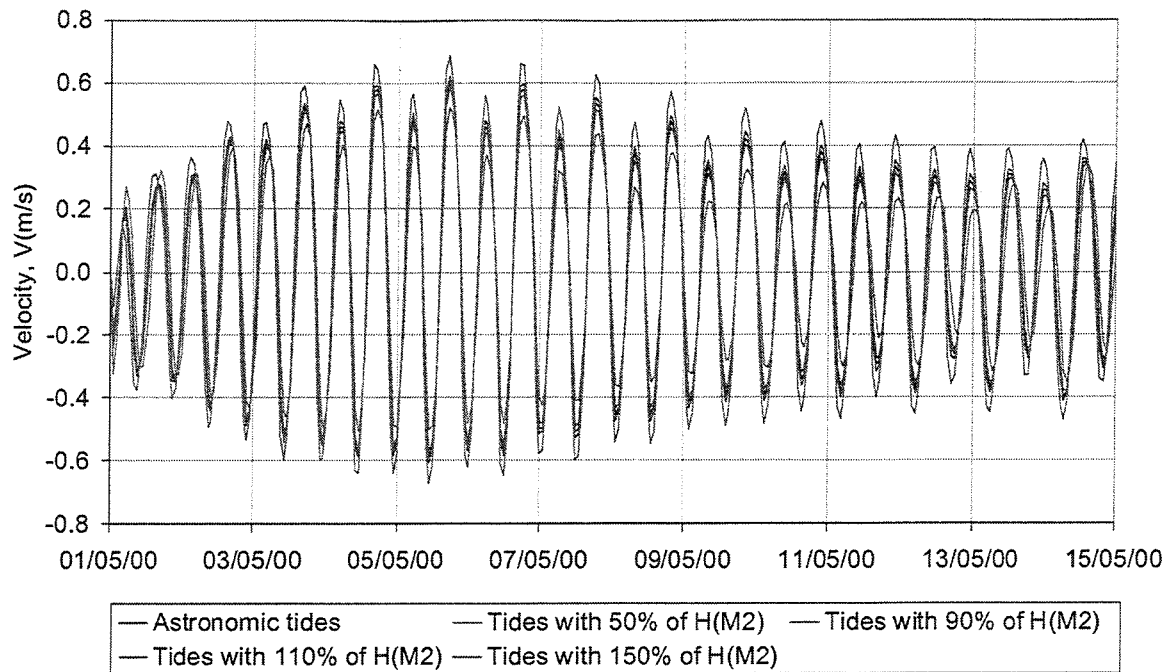


Figure II.7. Effect of the M2 tidal parameter on the maximum flow velocity at the Thuan An inlet in the dry season from January to August

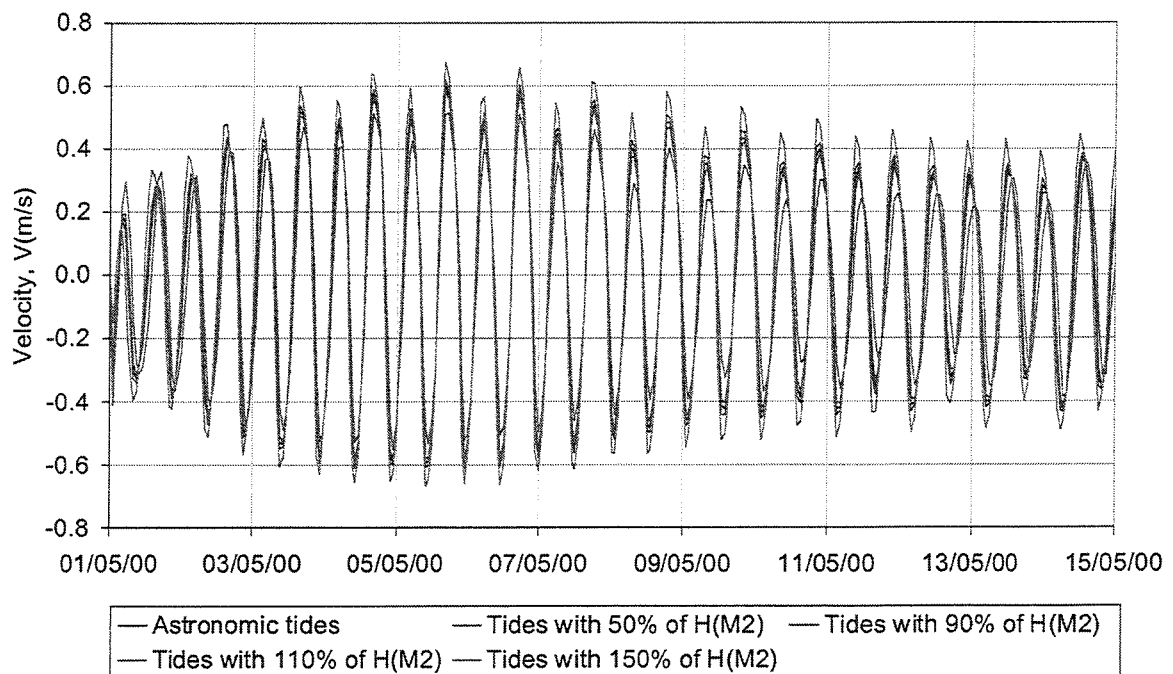


Figure II.8. Effect of the M2 tidal parameter on the maximum flow velocity at the Hoa Duan inlet in the dry season from January to August

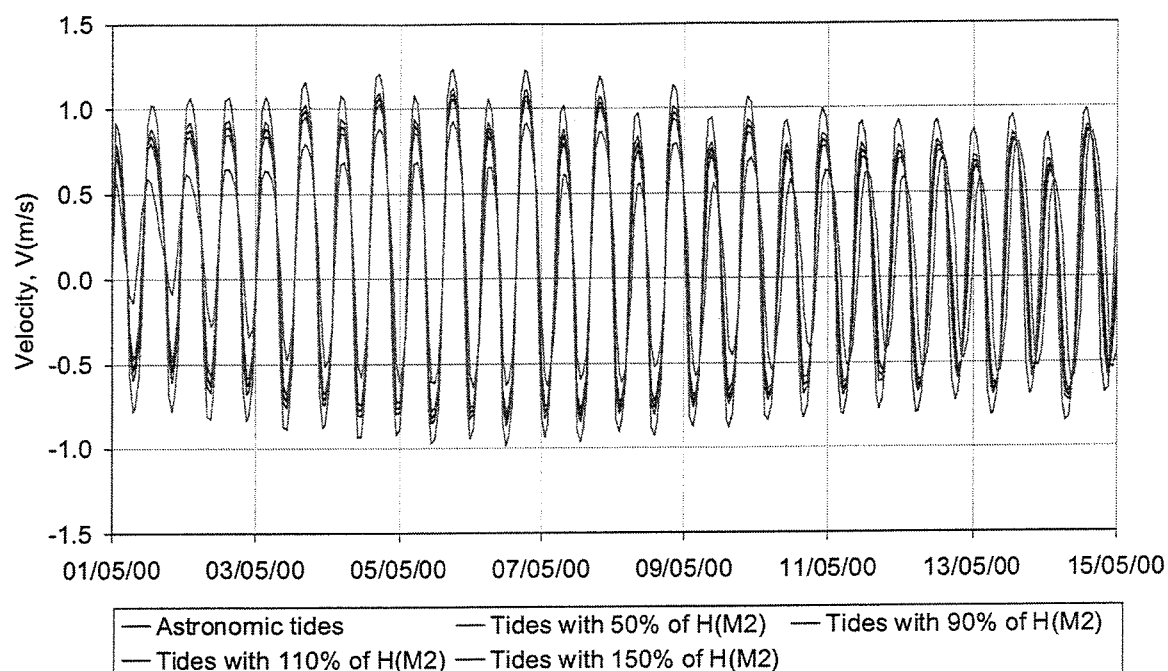


Figure II.9. Effect of the M2 tidal parameter on the maximum flow velocity at the Tu Hien inlet in the dry season from January to August

II.4.2. Effects of sea level rise

II.4.2.1. Case of the Hoa Duan inlet is closed (HD0)

Table II.19. Effect of sea level rise on the maximum flow velocity (m/s) in the lagoons and inlets

Scenario	Phase	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai	Thuan An	Hoa Duan	Tu Hien
SZ01-HD0: Only astro. tides	Ebb	0.03	0.19	0.72	0.26	0.15	0.25	0.08	0.84		1.10
	Flood	-0.02	-0.21	-0.65	-0.23	-0.13	-0.18	-0.07	-0.82		-0.85
SZ12-HD0: + Sea level rise of 0.1m	Ebb	0.03	0.19	0.72	0.26	0.15	0.25	0.08	0.86		1.11
	Flood	-0.02	-0.21	-0.67	-0.23	-0.13	-0.18	-0.07	-0.84		-0.86
SZ13-HD0: + Sea level rise of 0.2m	Ebb	0.03	0.18	0.72	0.27	0.15	0.26	0.08	0.88		1.12
	Flood	-0.01	-0.20	-0.68	-0.24	-0.14	-0.19	-0.07	-0.87		-0.86
SZ14-HD0: + Sea level rise of 0.5m	Ebb	0.02	0.17	0.70	0.28	0.16	0.27	0.07	0.92		1.15
	Flood	-0.01	-0.19	-0.69	-0.26	-0.14	-0.20	-0.06	-0.92		-0.89

Table II.20. Effect of sea level rise on the maximum water level (m) in the lagoons the dry season

Scenario	Value	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai
SZ01-HD0: Only astro. tides	Max	0.34	0.32	0.30	0.25	0.21	0.11	0.07
	Min	-0.30	-0.29	-0.33	-0.27	-0.20	-0.17	-0.17
	Average	-0.01	-0.01	-0.02	-0.02	-0.03	-0.04	-0.04
SZ12-HD0: + Sea level rise of 0.1m	Max	0.44	0.43	0.40	0.35	0.31	0.21	0.18
	Min	-0.22	-0.21	-0.23	-0.17	-0.11	-0.08	-0.07
	Average	0.09	0.09	0.08	0.08	0.07	0.06	0.06
SZ13-HD0: + Sea level rise of 0.2m	Max	0.55	0.53	0.50	0.45	0.41	0.32	0.28
	Min	-0.13	-0.12	-0.13	-0.07	-0.02	0.02	0.02
	Average	0.19	0.18	0.18	0.17	0.17	0.16	0.16
SZ14-HD0: + Sea level rise of 0.5m	Max	0.86	0.85	0.80	0.75	0.72	0.63	0.60
	Min	0.15	0.16	0.17	0.23	0.27	0.30	0.31
	Average	0.48	0.48	0.48	0.47	0.47	0.46	0.46

Table II.21. Effect of sea level rise on the maximum water level (m) at the inlets the dry season

Scenario	Value	Water level (m) at inlets			Difference in water level (m)		
		Thuan An	Hoa Duan	Tu Hien	Tam Giang – Cau Hai	Tam Giang – Thuan An	Cau Hai – Tu Hien
SZ01-HD0: Only astro. tides	Max	0.31	0.27	0.09	0.26	0.27	0.21
	Min	-0.34	-0.30	-0.22	-0.18	-0.25	-0.14
	Average	-0.02	-0.02	-0.06	0.03	0.01	0.02
SZ12-HD0: + Sea level rise of 0.1m	Max	0.41	0.37	0.19	0.27	0.26	0.21
	Min	-0.24	-0.20	-0.12	-0.19	-0.25	-0.14
	Average	0.08	0.08	0.04	0.03	0.01	0.02
SZ13-HD0: + Sea level rise of 0.2m	Max	0.51	0.47	0.29	0.28	0.25	0.21
	Min	-0.14	-0.09	-0.02	-0.20	-0.24	-0.14
	Average	0.18	0.18	0.14	0.03	0.01	0.02
SZ14-HD0: + Sea level rise of 0.5m	Max	0.81	0.77	0.59	0.36	0.21	0.22
	Min	0.16	0.21	0.27	-0.23	-0.48	-0.21
	Average	0.48	0.48	0.44	0.03	0.00	0.02

Table II.22. Effect of sea level rise on the maximum flow discharge (m^3/s) in the lagoons and inlets

Scenario	Phase	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai	Thuan An	Hoa Duan	Tu Hien
SZ01-HD0: Only astro. tides	Ebb	122	540	1306	1027	758	635	734	3246		866
	Flood	-97	-588	-1306	-771	-557	-422	-564	-3332		-729
SZ12-HD0: + Sea level rise of 0.1m	Ebb	128	567	1355	1083	812	676	766	3364		903
	Flood	-101	-608	-1369	-829	-602	-456	-588	-3471		-758
SZ13-HD0: + Sea level rise of 0.2m	Ebb	134	595	1408	1139	866	717	798	3475		940
	Flood	-104	-626	-1427	-886	-646	-492	-613	-3604		-786
SZ14-HD0: + Sea level rise of 0.5m	Ebb	147	661	1549	1303	1023	846	896	3781		1055
	Flood	-113	-682	-1578	-1063	-786	-605	-684	-3969		-878

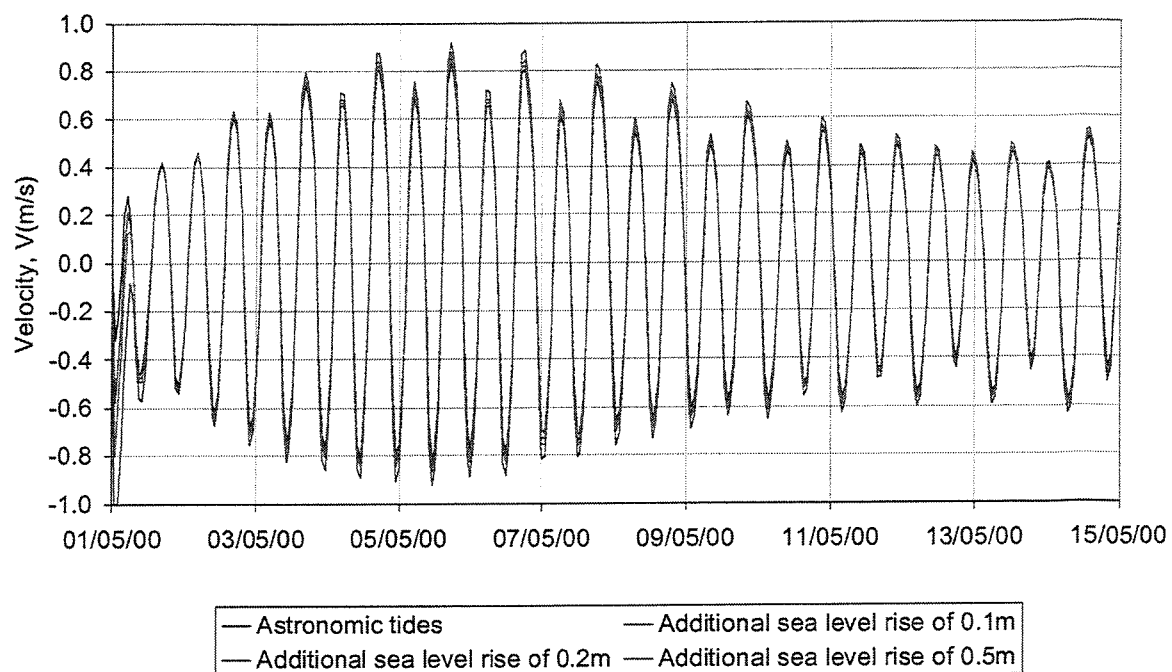


Figure II.10. Effect of sea level rise on the maximum flow velocity at the Thuan An the dry season from January to August with the Hoa Duan inlet is closed

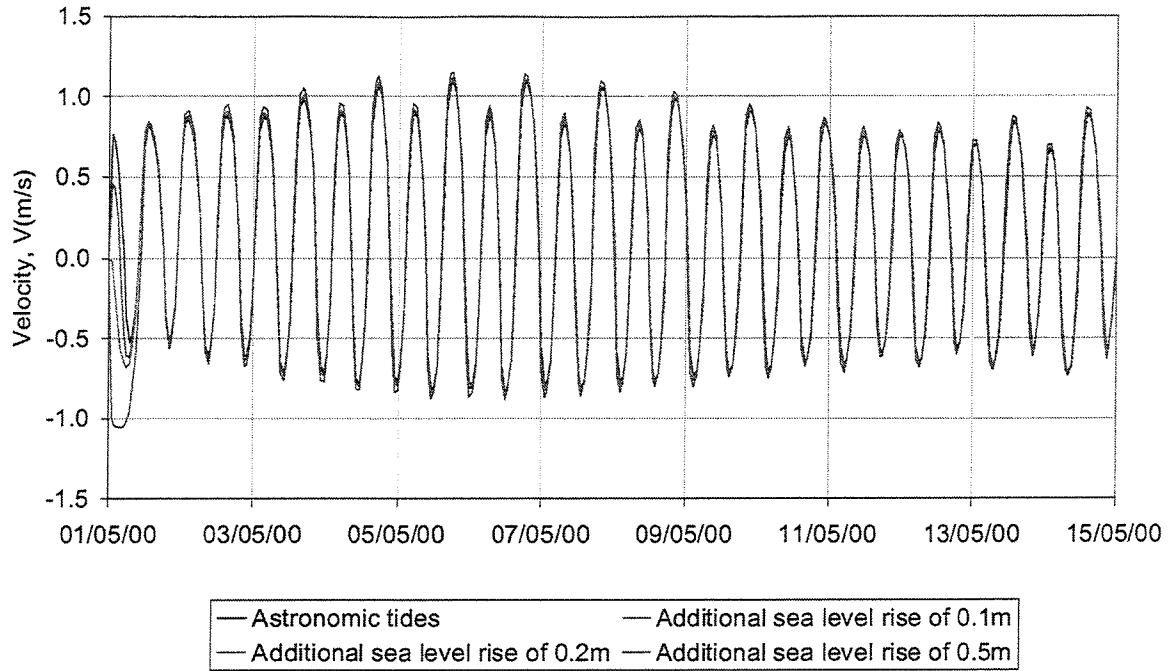


Figure II.11. Effect of sea level rise on the maximum flow velocity at the Tu Hien the dry season from January to August with the Hoa Duan inlet is closed

II.4.2.2. Case of the Hoa Duan inlet is opened (HD1)

Table II.23. Effect of sea level rise on the maximum flow velocity (m/s) in the lagoons and inlets

Scenario	Phase	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai	Thuan An	Hoa Duan	Tu Hien
SZ01+HD1: Astro. tides	Ebb	0.03	0.19	0.74	0.29	0.16	0.27	0.08	0.60	0.60	1.09
	Flood	-0.02	-0.21	-0.67	-0.25	-0.14	-0.18	-0.07	-0.59	-0.60	-0.84
SZ12+HD1: Sea level rise of 0.1m	Ebb	0.03	0.19	0.74	0.29	0.16	0.27	0.08	0.62	0.61	1.10
	Flood	-0.02	-0.21	-0.68	-0.25	-0.14	-0.19	-0.07	-0.61	-0.61	-0.84
SZ13+HD1: Sea level rise of 0.2m	Ebb	0.03	0.19	0.73	0.30	0.16	0.28	0.07	0.63	0.62	1.11
	Flood	-0.02	-0.21	-0.69	-0.26	-0.15	-0.20	-0.06	-0.62	-0.63	-0.85
SZ14+HD1: sea level rise of 0.5m	Ebb	0.02	0.18	0.71	0.31	0.17	0.29	0.07	0.66	0.64	1.14
	Flood	-0.01	-0.20	-0.70	-0.28	-0.16	-0.22	-0.06	-0.66	-0.66	-0.88

Table II.24. Effect of sea level rise on the maximum water level (m) in the lagoons the dry season

Scenario	Value	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai
SZ01+HD1: Astronomical tides	Max	0.34	0.33	0.31	0.27	0.23	0.12	0.08
	Min	-0.31	-0.30	-0.33	-0.29	-0.21	-0.18	-0.17
	Average	-0.01	-0.01	-0.02	-0.02	-0.02	-0.04	-0.04
SZ12+HD1: Sea level rise of 0.1m	Max	0.45	0.43	0.41	0.37	0.33	0.23	0.19
	Min	-0.22	-0.21	-0.24	-0.19	-0.12	-0.08	-0.08
	Average	0.09	0.09	0.08	0.08	0.08	0.06	0.06
SZ13+HD1: Sea level rise of 0.2m	Max	0.55	0.54	0.51	0.47	0.44	0.33	0.29
	Min	-0.13	-0.12	-0.14	-0.09	-0.02	0.02	0.02
	Average	0.19	0.18	0.18	0.18	0.18	0.16	0.16
SZ14+HD1: sea level rise of 0.5m	Max	0.87	0.87	0.82	0.77	0.75	0.64	0.61
	Min	0.14	0.15	0.16	0.21	0.25	0.30	0.30
	Average	0.48	0.48	0.48	0.48	0.47	0.46	0.46

Table II.25. Effect of sea level rise on the maximum water level (m) at the inlets the dry season

Scenario	Value	Water level (m) at inlets			Difference in water level (m)		
		Thuan An	Hoa Duan	Tu Hien	Tam Giang – Cau Hai	Tam Giang – Thuan An	Cau Hai – Tu Hien
SZ01+HD1: Astronomical tides	Max	0.32	0.32	0.09	0.26	0.27	0.20
	Min	-0.34	-0.34	-0.22	-0.18	-0.25	-0.14
	Average	-0.02	-0.02	-0.06	0.03	0.01	0.02
SZ12+HD1: Sea level rise of 0.1m	Max	0.42	0.42	0.19	0.27	0.26	0.20
	Min	-0.24	-0.24	-0.12	-0.19	-0.25	-0.14
	Average	0.08	0.08	0.04	0.03	0.01	0.02
SZ13+HD1: Sea level rise of 0.2m	Max	0.52	0.52	0.29	0.27	0.24	0.21
	Min	-0.14	-0.14	-0.03	-0.20	-0.24	-0.14
	Average	0.18	0.18	0.14	0.03	0.01	0.02
SZ14+HD1: sea level rise of 0.5m	Max	0.82	0.81	0.60	0.36	0.21	0.22
	Min	0.16	0.16	0.27	-0.22	-0.49	-0.21
	Average	0.48	0.48	0.44	0.03	0.00	0.02

Table II.26. Effect of sea level rise on the maximum flow discharge (m^3/s) in the lagoons and inlets

Scenario	Phase	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai	Thuan An	Hoa Duan	Tu Hien
SZ01+HD1: Astronomical tides	Ebb	125	552	1331	1166	840	679	715	2335	1121	860
	Flood	-100	-599	-1339	-828	-590	-444	-542	-2402	-1171	-718
SZ12+HD1: Sea level rise of 0.1m	Ebb	131	584	1395	1232	897	727	747	2417	1166	896
	Flood	-104	-620	-1404	-893	-644	-483	-562	-2504	-1224	-745
SZ13+HD1: Sea level rise of 0.2m	Ebb	137	612	1454	1297	954	774	779	2495	1208	936
	Flood	-107	-639	-1463	-958	-699	-523	-581	-2601	-1276	-776
SZ14+HD1: sea level rise of 0.5m	Ebb	150	679	1600	1487	1117	920	879	2701	1324	1057
	Flood	-118	-705	-1626	-1160	-863	-648	-646	-2857	-1419	-870

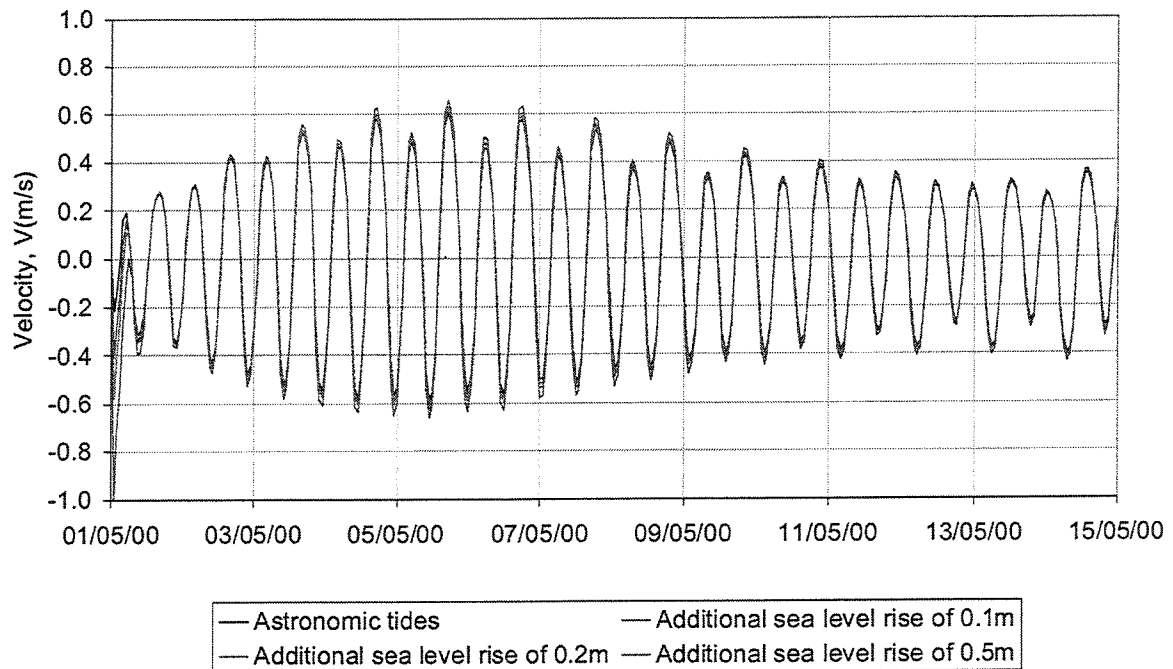


Figure II.12. Effect of sea level rise on the maximum flow velocity at the Thuan An the dry season from January to August with the Hoa Duan inlet is opened

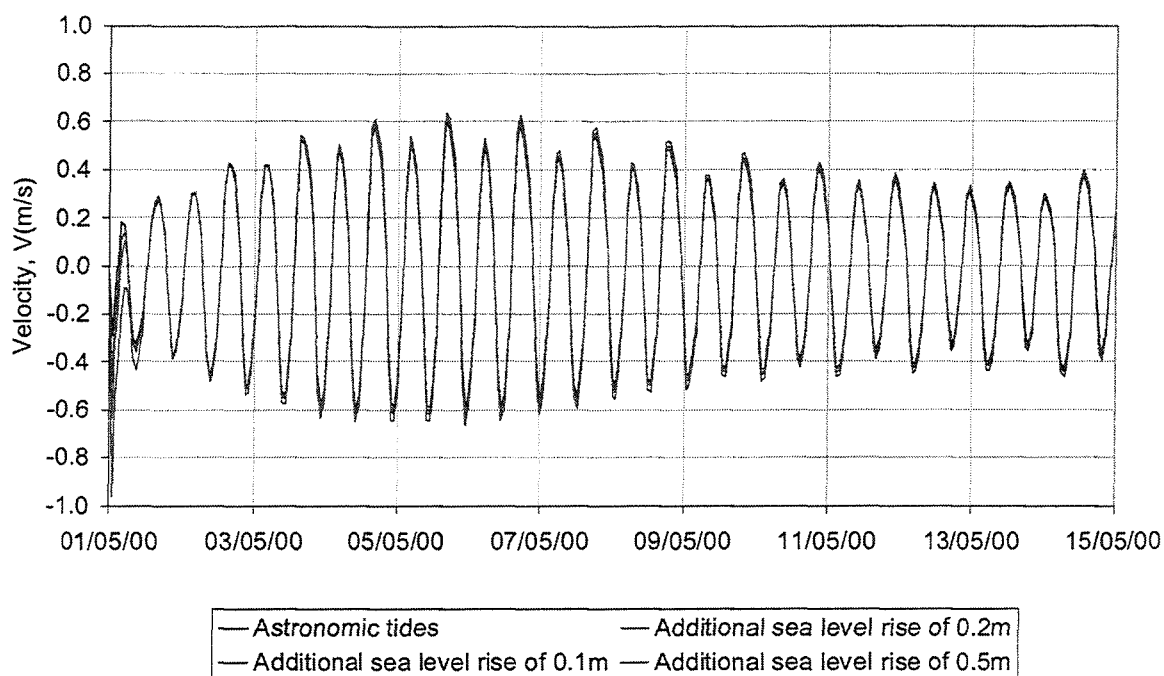


Figure II.13. Effect of sea level rise on the maximum flow velocity at the Hoa Duan the dry season from January to August with the Hoa Duan inlet is opened

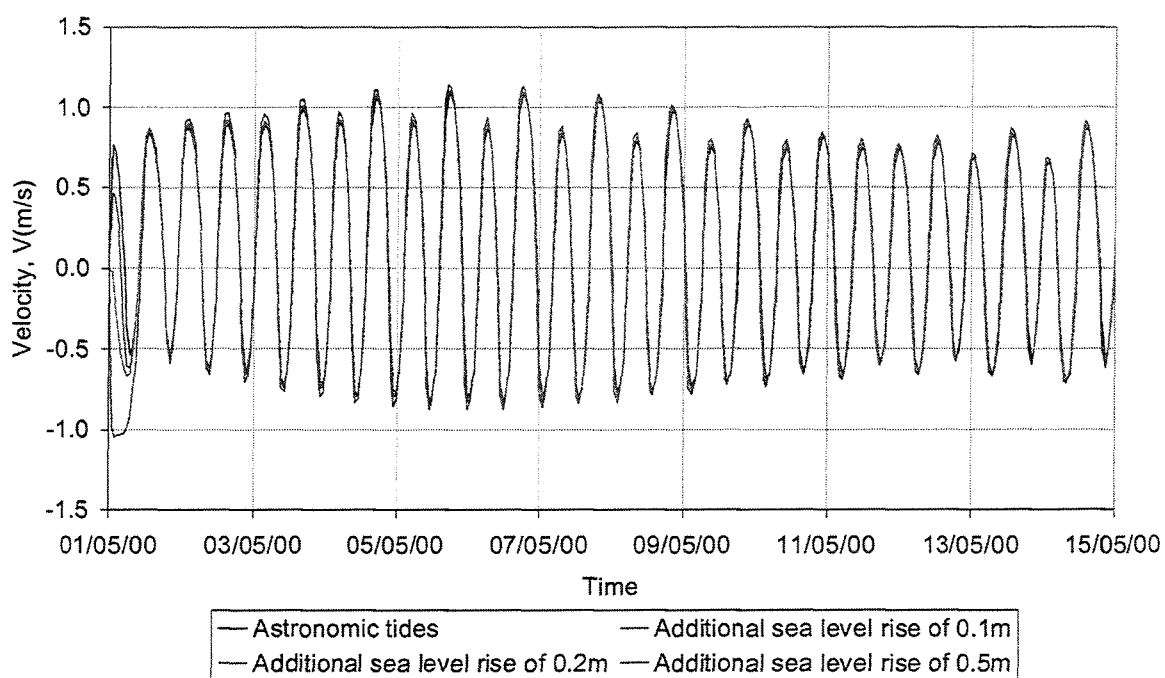


Figure II.14. Effect of sea level rise on the maximum flow velocity at the Tu Hien the dry season from January to August with the Hoa Duan inlet is opened

II.4.3. Effects of inlet openings

Table II.27. Effect of inlet openings on the maximum flow velocity (m/s) in the lagoons and inlets

Inlet opening scenario	Phase	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai	Thuan An	Hoa Duan	Tu Hien
SO01: Thuan An:B=535m; Hoa Duan:B=420m	Ebb	0.03	0.19	0.74	0.29	0.16	0.27	0.08	0.60	0.60	1.09
	Flood	-0.02	-0.21	-0.67	-0.25	-0.14	-0.18	-0.07	-0.59	-0.60	-0.84
SO02: Thuan An:B=535m; Hoa Duan: closed	Ebb	0.03	0.19	0.72	0.26	0.15	0.25	0.08	0.84		1.10
	Flood	-0.02	-0.21	-0.65	-0.23	-0.13	-0.18	-0.07	-0.82		-0.85
SO03: Thuan An: closed; Hoa Duan:B=420m	Ebb	0.02	0.13	0.47	0.21	0.13	0.21	0.08		1.26	1.08
	Flood	-0.01	-0.14	-0.45	-0.18	-0.11	-0.14	-0.07		-1.20	-0.84
SO04: Thuan An:B=344m; Hoa Duan:B=217m	Ebb	0.03	0.15	0.54	0.21	0.13	0.22	0.08	1.32	1.23	1.09
	Flood	-0.01	-0.17	-0.51	-0.18	-0.11	-0.15	-0.07	-1.20	-1.16	-0.84
SO05: Thuan An:B=344m; Hoa Duan: closed	Ebb	0.02	0.13	0.46	0.17	0.10	0.21	0.08	1.51		1.08
	Flood	-0.01	-0.14	-0.44	-0.14	-0.08	-0.13	-0.07	-1.39		-0.84
SO06: Thuan An: closed; Hoa Duan:B=217m	Ebb	0.02	0.07	0.22	0.11	0.07	0.17	0.08		1.60	1.04
	Flood	0.00	-0.07	-0.22	-0.07	-0.04	-0.05	-0.06		-1.59	-0.79

Table II.28. Effect of inlet openings on the maximum water level (m) in the lagoons

Inlet opening scenario	Value	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai
SO01: Thuan An:B=535m; Hoa Duan:B=420m; Tu Hien:B=189m	Max	0.34	0.33	0.31	0.27	0.23	0.12	0.08
	Min	-0.31	-0.30	-0.33	-0.29	-0.21	-0.18	-0.17
	Average	-0.01	-0.01	-0.02	-0.02	-0.02	-0.04	-0.04
SO02: Thuan An:B=535m; Hoa Duan: closed; Tu Hien:B=189m	Max	0.34	0.32	0.30	0.25	0.21	0.11	0.07
	Min	-0.30	-0.29	-0.33	-0.27	-0.20	-0.17	-0.17
	Average	-0.01	-0.01	-0.02	-0.02	-0.03	-0.04	-0.04
SO03: Thuan An: closed; Hoa Duan:B=420m; Tu Hien:B=189m	Max	0.24	0.23	0.20	0.20	0.17	0.10	0.07
	Min	-0.22	-0.21	-0.20	-0.21	-0.17	-0.16	-0.16
	Average	-0.01	-0.01	-0.01	-0.02	-0.02	-0.04	-0.04
SO04: Thuan An:B=344m; Hoa Duan:B=217m; Tu Hien:B=189m	Max	0.27	0.26	0.23	0.21	0.17	0.10	0.07
	Min	-0.24	-0.24	-0.24	-0.22	-0.18	-0.17	-0.16
	Average	-0.01	-0.01	-0.02	-0.02	-0.02	-0.04	-0.04
SO05: Thuan An:B=344m; Hoa Duan: closed; Tu Hien:B=189m	Max	0.23	0.22	0.19	0.16	0.14	0.08	0.06
	Min	-0.21	-0.21	-0.20	-0.18	-0.16	-0.15	-0.15
	Average	-0.01	-0.01	-0.02	-0.02	-0.03	-0.04	-0.04
SO06: Thuan An: closed; Hoa Duan:B=217m; Tu Hien:B=189m	Max	0.12	0.12	0.10	0.09	0.09	0.07	0.06
	Min	-0.12	-0.12	-0.11	-0.11	-0.11	-0.13	-0.13
	Average	-0.02	-0.02	-0.02	-0.02	-0.03	-0.03	-0.04

Table II.29. Effect of inlet openings on the maximum water level (m) at the inlets

Inlet opening scenario	Value	Water level (m) at inlets			Difference in water level (m)		
		Thuan An	Hoa Duan	Tu Hien	Tam Giang – Cau Hai	Tam Giang – Thuan An	Cau Hai – Tu Hien
SO01: Thuan An:B=535m; Hoa Duan:B=420m; Tu Hien:B=189m	Max	0.32	0.32	0.09	0.26	0.27	0.20
	Min	-0.34	-0.34	-0.22	-0.18	-0.25	-0.14
	Average	-0.02	-0.02	-0.06	0.03	0.01	0.02
SO02: Thuan An:B=535m; Hoa Duan: closed; Tu Hien:B=189m	Max	0.31	0.27	0.09	0.26	0.27	0.21
	Min	-0.34	-0.30	-0.22	-0.18	-0.25	-0.14
	Average	-0.02	-0.02	-0.06	0.03	0.01	0.02
SO03: Thuan An: closed; Hoa Duan:B=420m; Tu Hien:B=189m	Max	0.19	0.27	0.09	0.17	0.11	0.20
	Min	-0.20	-0.28	-0.22	-0.08	-0.12	-0.13
	Average	-0.01	-0.02	-0.06	0.03	0.00	0.02
SO04: Thuan An:B=344m; Hoa Duan:B=217m; Tu Hien:B=189m	Max	0.32	0.32	0.09	0.19	0.30	0.20
	Min	-0.34	-0.34	-0.22	-0.12	-0.27	-0.14
	Average	-0.02	-0.02	-0.06	0.03	0.01	0.02
SO05: Thuan An:B=344m; Hoa Duan: closed; Tu Hien:B=189m	Max	0.32	0.17	0.09	0.17	0.31	0.20
	Min	-0.34	-0.19	-0.22	-0.09	-0.27	-0.14
	Average	-0.02	-0.02	-0.06	0.03	0.01	0.02
SO06: Thuan An: closed; Hoa Duan:B=217m; Tu Hien:B=189m	Max	0.10	0.31	0.09	0.12	0.04	0.19
	Min	-0.10	-0.33	-0.22	-0.06	-0.05	-0.12
	Average	-0.02	-0.02	-0.06	0.02	0.00	0.02

Table II.30. Effect of inlet openings on the maximum flow discharge (m³/s) in the lagoons and inlets

Inlet opening scenario	Phase	Tam Giang (North)	Tam Giang (Center)	Tam Giang (South)	Thanh Lam	Thuy Tu (North)	Thuy Tu (South)	Cau Hai	Thuan An	Hoa Duan	Tu Hien
SO01: Thuan An:B=535m; Hoa Duan:B=420m	Ebb	125	552	1331	1166	840	679	715	2334	1122	860
	Flood	-100	-599	-1339	-828	-590	-444	-542	-2401	-1172	-718
SO02: Thuan An:B=535m; Hoa Duan: closed	Ebb	122	540	1306	1027	758	635	734	3246		866
	Flood	-97	-588	-1306	-771	-557	-422	-564	-3332		-729
SO03: Thuan An: closed; Hoa Duan:B=420m	Ebb	95	389	869	820	634	530	710		2269	855
	Flood	-58	-386	-878	-631	-460	-343	-532		-2352	-718
SO04: Thuan An:B=344m; Hoa Duan:B=217m	Ebb	106	449	1014	860	645	551	717	1730	695	858
	Flood	-67	-437	-1003	-644	-466	-352	-541	-1804	-747	-721
SO05: Thuan An:B=344m; Hoa Duan: closed	Ebb	95	389	859	678	522	498	712	1985		850
	Flood	-57	-374	-847	-503	-368	-312	-554	-2081		-720
SO06: Thuan An: closed; Hoa Duan:B=217m	Ebb	61	207	425	412	368	398	654		900	818
	Flood	-22	-196	-409	-252	-160	-122	-479		-1009	-679

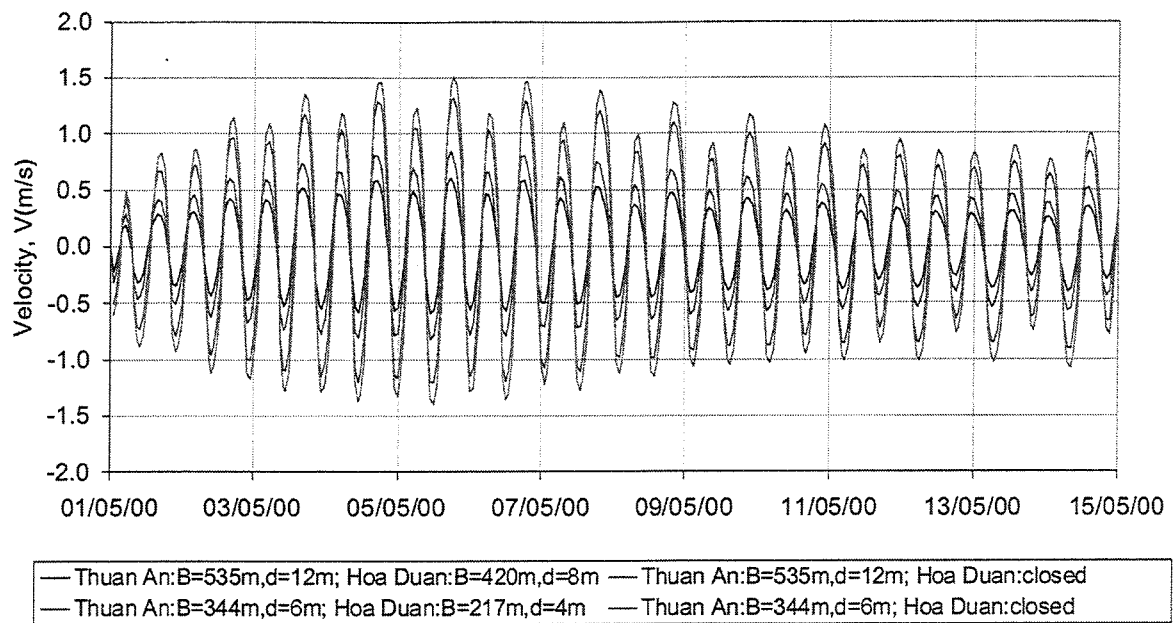


Figure II.15. Effect of inlet openings on the maximum flow velocity at the Thuan An inlet in the dry season from January to August

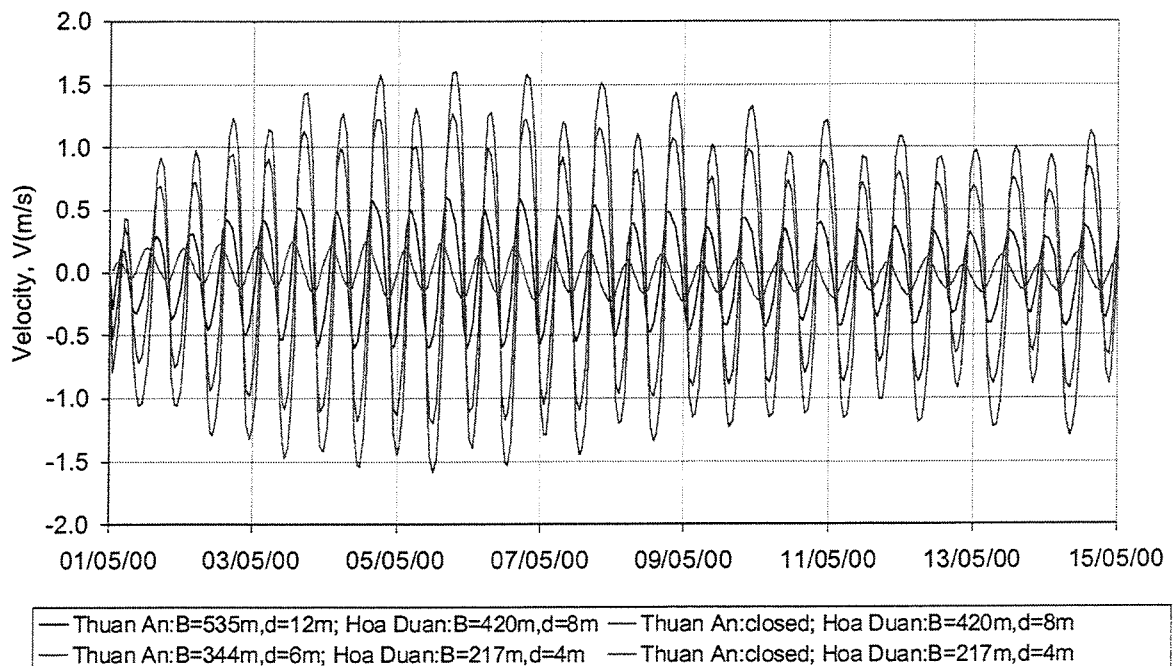


Figure II.16. Effect of inlet openings on the maximum flow velocity at the Hoa Duan inlet in the dry season from January to August

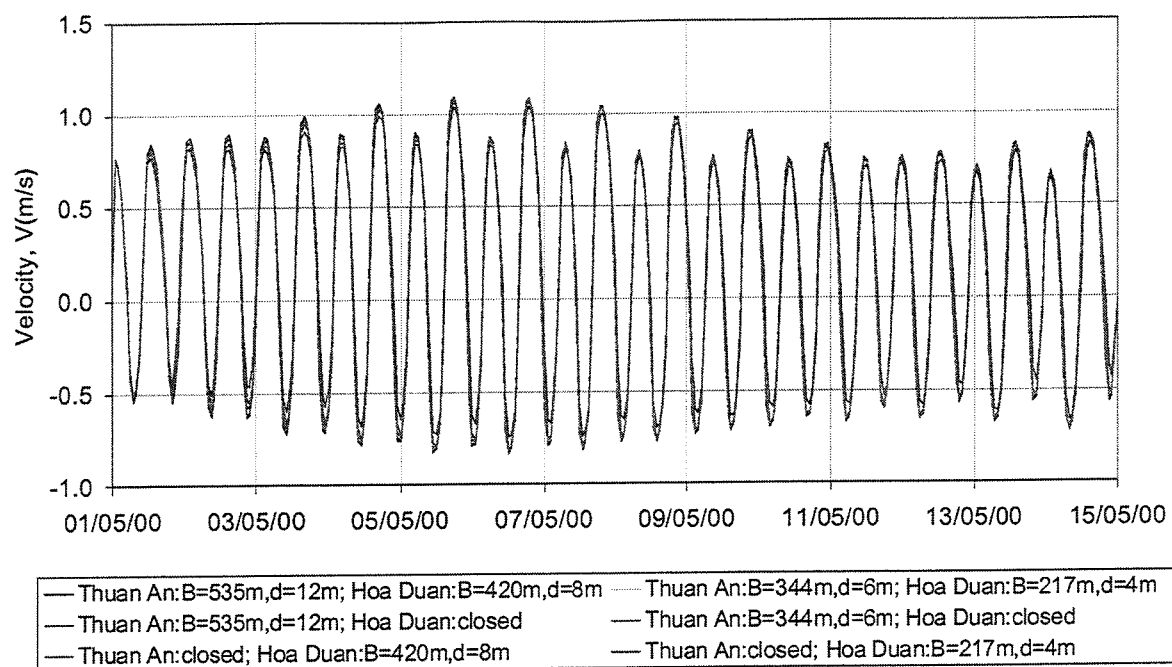


Figure II.17. Effect of inlet openings on the maximum flow velocity at the Tu Hien inlet in the dry season from January to August

